Functional Evaluation of Robot End-Point Assisted Gait re-Education in Chronic Stroke Survivors

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***Abstract*— Gait re-education is a primary rehabilitation goal after stroke. In this study, we used instrumented gait analysis for evaluating the outcomes of gait training assisted by an endpoint robot in a population of six chronic stroke survivors. The preliminary results, based on spatial-temporal and kinematic analysis, suggest that (a) self-placed walking speed increases, with an improvement of both length and duration of the stride, (b) balance increases during standing and walking, (c) the non-affected side becomes less involved in attempting to correct for the deficiencies of the affected side, thus reducing the importance of compensatory strategies.**

***Keywords*— gait training, robot therapy, stroke survivors**

I. INTRODUCTION

Stroke is one of most prevalent causes of impairment in many countries and its incidence continues to rise[1]. Nearly 67% of all stroke survivors are left with physical disability and approximately 25% of them lose their independence [2]. Common symptoms, typically exhibited by the side contralateral to the hemispheric lesion, are spasticity [3, 4], abnormal synergies [5, 6], muscle weakness [7], incorrect regulation of inter-joint torque, incorrect timing of action sequences [8], decreased joint range of motion [9, 10], loss of inter-joint coordination [11], and decreased sensory sensitivity, with particular emphasis on proprioception [12]. In order to regain as much as possible the ability to perform tasks that once were straightforward, stroke survivors undergo a profound reorganization of their neural control. In their effort to quickly regain independence, impaired individuals focus on the recovery of activities of daily living (ADLs) such as standing, walking, reaching, and grasping. This often leads to the development of compensatory strategies that, even when sufficient to carry out ADLs, tend to be stereotyped and energetically inefficient. In a long term perspective this strategy may cause incorrect postures, weaken underutilized muscles, and reduce with time the possibility to recover different abilities [13].

Re-education of walking ability is one of the primary goals of the rehabilitative treatment. Nowadays, robots that assist patient during gait are used in the clinical practice. There are several robot models that differ for mechanical design – e.g. exoskeleton vs. endpoint robot - and exercise modalities (see [14] and [15] for a review).

A 2007 Cochrane review [16] compared two robots for electromechanical gait training and suggested that they could improve independent walking. An additional more recent report [17] confirms these results and suggests that robot assisted gait training, combined with traditional physical therapy, can improve the recovery process after stroke. However, as highlighted by [14, 18], remarkable effects are reported in acute patients, but less relevant results in chronic stroke survivors.

As rehabilitators, we think that chronic disabilities should not be considered as definitive and that there is always a margin for improvements. Moreover, the chronic condition is a greater challenge in rehabilitation and presents well-defined patterns that are easier to investigate in this population with respect to the acute one. This is the case of the compensatory strategies that for chronic survivors often represent a well-established behavior to be reduced or compensated by the therapy, in favor of the best “true” functional recovery [13] for a long-term perspective. In robot assisted training, this problem is more interesting for gait re-education than for upper arm movements, were often only the paretic arm is involved in the treatment [19], because of the unavoidable coupling between the two limbs during walking.

Here we report the results of a preliminary investigation of the efficacy of gait re-education by means of an endpoint robot [20] with a group of six chronic stroke survivors. We focused not only on spatial and temporal variables, but also on the kinematic parameters at the level of the pelvis, hip, knee, and ankle joints. We specifically investigated the effects of robot training in the different planes - sagittal, frontal, transverse - and the interaction between the motion of the “affected” and “not affected” limb. This is a main element of novelty of this study as well as the focus on the postural improvement of the pelvis.

II. METHODS

This study investigated the reorganization of walking abilities induced by up to 20 sessions of robot mediated gait training. The protocol was based on training exercises with progressively increasing difficulty, regulated by the therapist according to the subjects' residual abilities and the progress due to training.

A. Subjects

Seven chronic stroke survivors (Table I) were enrolled in this study after signing informed consent conformed to the ethical standards of the 1964 Declaration of Helsinki and to ethical bylaws of the International Association of Bobath Instructors (IBITA: art. IV of the statute). Their anthropometric and etiologic characteristics are listed in Table I. Subjects were selected among the outpatients of the Rehabilitation and Functional Reeducation Unit, Santa Corona Hospital of Pietra Ligure, Savona, Italy.

Inclusion criteria were:

- Chronic stroke (more than 1 year after the disease onset);
- Mini-Mental State Examination (MMSE) >24 [21];
- No Botulinum toxin injection in the last 4 months;
- No functional surgery in the last 6 months;
- Stable clinical conditions (at least three months before entering robot therapy).

The walking ability of all subjects was evaluated by using the walking handicap scale [22].

Drop out: Subject S7 did not participate to the post-treatment evaluation and therefore his data are not considered further in this study.

B. Training: robot mediated gait re-education

The rehabilitation treatment aimed to train an important functional ability such as walking. Subjects participated in up to 20 sessions, with a maximum duration of 45 minutes each, 3-4 times per week. Since the goal of the first session was to familiarize participants with the robot, the corresponding data are not included in the training evaluation. Duration and intensity of training sessions, including the amount of break-time during training, were regulated depending on individual subject features, such as level of impairment, presence of weakness or fatigue, etc. Subjects stood on a walking robot (G-EO System, RehaTechnology AG, 4600 Olten, Switzerland) [20], specifically designed for gait re-education. This device is an end-point robot, i.e, the force assistance provided by the device is transmitted to the subjects only at the feet by means of the robot pedals. The movements of ankle, knee and hip joints were not constrained by any holder. Subjects could lie on a panel positioned on the back of their body at the pelvis level. We used the robot body weight–support (BWS), just as security system in order to prevent falling, no full or partial support was provided. During training subjects received visual feedback about the weight distribution on their feet, namely plantar pressure during walking was displayed on a wall in front of them 2 meters away.

The protocol was based on the following concepts:

- Integration of robot therapy with physiotherapy;
- Adaptive training paradigm, based on a progressively increasing difficulty index.

An experienced physical therapist supervised the rehabilitation sessions and selected the level of task difficulties and assistance for each subject. The robot allows three different training modalities with increasing level of difficulty, namely:

- *Passive*: the end-effector movement is robot-driven and does not require any contribution from the subject;
- *Adaptive*: the movement is completely driven by the subject.
- *Adaptive plus*: the movement is driven by the subjects, when the active contribution of the subject is above a selected threshold; otherwise, the robot comes into action to help the patient;

Training started with a passive exercise in order to allow the subjects to familiarize with the robot. Gait speed was initially fixed at 0.8 km/h and was increased across sessions, depending on the individual subject's performance, up to a maximum value of 2.3 km/h. The therapist changed the exercise modality, the walking speed, and the step length according to the subjects' residual abilities and the therapy induced improvement, if present. The training was planned with a "challenge-based approach", i.e. with the goal to promote an increasing voluntary control contribution from the subject by maintaining the exercise as challenging as possible: not too easy, in order to avoid slacking, but neither too difficult, in order to avoid frustration.

TABLE I.
SUBJECTS' DATA

	A	D [y]	G	E	W [kg]	Ht [cm]	P L	W H S	A
S1	47	6	F	H	60	165	L	5	N
S2	43	2	F	I	57	160	R	5	C
S3	60	8	F	H	77	158	R	3	C
S4	69	5	F	I	80	160	R	4	C
S5	41	6	F	I	47	163	R	5	N
S6	75	8	M	H	76	172	R	4	C
S7	61	1	M	I	70	178	L	4	N

A=Age: years. D= duration of disease (months) G=Gender: M=male, F=female; E=Etiology: I=Ischemic, H=Hemorrhagic; PL=paretic leg L=Left, R=Right; W=Weight [kg]; Ht=Height [cm]; A =Walking Aids: N nothing; C=cane; WHS= Walking Handicap Scale score (1-6).

C. Assesment

The assessment goal was to verify if adaptive gait training could induce detectable changes of the walking ability in chronic stroke survivors. The evaluation was divided into two parts. The first part consisted of four clinical tests, aimed at evaluating the subject's walking speed and resistance under different conditions:

A. 10 meter walk test (10MWT) at the preferred speed [23][1];
B. 10 meter walk test at maximum speed[23];
C. 6 minute walk test (6mWT) [24];
D. Time Up and Go Test (TUG) [25].

The second part of the evaluation procedure was instrumental and used a motion capture system (SMART DX, BTS Bioengineering, Italy) with 8 infrared cameras, 2 force

[1] In this test, as well as in test B, subjects were asked to walk in a 10 m pathway but only the time in the central 6 m was considered.

platforms (Kistler) and 2 video cameras (Vixta). The infrared markers were positioned according to the Davis protocol [26]. Data were collected at a sample frequency of 100 Hz. Subjects were asked to walk for 8 meters at their preferred speed and with their normal walking patterns, namely the patterns they use in the everyday life (see Table 1). For each subject the same walking conditions were used in pre and post treatment evaluation. Kinematic data were recorded and stored along the middle portion of the pathway (3m). In this area two force platforms measured the foot ground reaction forces. Each patient was requested to perform at least 5 walking trials, with a minimum of three trials, providing a clear and complete foot-force plate contact. We chose the first three complete trials of a session in order to calculate the mean data. For each trial, we considered the gait cycle containing the full contact with the force platform for both legs. This evaluation was carried out in the Santa Corona motion analysis laboratory by a physician and a bioengineer, both blind with respect to the goal of this study and to the rehabilitation treatment performed. Kinetic and kinematic variables were first estimated by using the SMART Analyzer program (BTS Bioengineering, Italy) and afterward they were further analyzed with Matlab (MathWorks, Natick, MA, US).

The clinical assessments (A-B-D) were performed at three different times of the training protocol: before initiation (T0), at half time (T1), and after the end (T2). The 6mWT, the TUG and the instrumental evaluation were carried out at T0 and T2.

Outcome measures. As primary outcome we selected the walking speed that was measured both with clinical tests and instrumented gait analysis. As secondary outcomes we looked at the spatial-temporal and kinematic measures provided by the instrumented evaluation.

Spatial-temporal parameters. We evaluated the following parameters while subjects were walking at their spontaneous, self-paced speed: Average speed, Cadence, Stride time, Stride length, Foot width, Step, and Speed progression of the body on the paretic foot [27]. This measure was computed as the speed of the marker on the sacrum when the not paretic leg was on the swing phase i.e. when the body progression relied on the paretic foot. We also measured the step length and the swing time and speed, the time of single and double stance on both feet.

Kinematic parameters. We looked at the movements in the frontal, sagittal, and transversal plane at the level of the pelvis and the hip, knee, and ankle joints.

Working hypotheses. First, we verified if the robot assisted gait training induced any changes in the spatio-temporal and kinematic variables estimated by instrumented gait analyses. Specifically, we tested the hypothesis that changes - if any - would be more in the sagittal planes than in the transverse.

Next, we looked at both the "affected" (Affected Limb, AL) and "not affected" side of the body. The compensatory strategies that characterize the recovery after stroke and the fact that during gait the two limbs are coupled determine kinematic patterns that are different from the normal ones also in the ipsilateral side of the hemispheric lesion. We specifically focused on evaluating the changes - if any - on the "Not affected Limb" (NL). Finally, we tried to detect if the performance during training were correlated with the eventual changes in the walking ability of the subjects between pre and post robot assisted training.

Statistical analysis

The small sample size (6 subjects) of our population does not allow appropriate full statistical analyses of the data. However, consistencies were tested using a Wilcoxon signed-rank test with 6 matched pairs[28, 29]. The signed-rank test detected difference between the T0 and T2 evaluations either when:

- all six differences were in the same direction (P*** = 0.03);
- 5 out of 6 differences were in the same direction with the non-conforming difference being the smallest in magnitude (P** = 0.06);
- 5 out of 6 differences were in the same direction with the non-conforming difference being the second smallest in magnitude (P* = 0.09).

Therefore each of these three cases indicated strong and consistent differences between evaluations before and after treatment.

We used the Matlab function signrank, with p = signrank (x,y) where x were the data pre-treatment, y the data post-treatment, and p the p-value of a paired two-sided test for the null hypothesis that x-y comes from a distribution with zero median. In order to understand if the changes in performance during gait training were correlated with modification of spatial, temporal, and kinematic variables of the gait, we looked at the correlation among the variation of the training parameters (walking distance: final vs. initial) and the evaluation (post vs. pre) of the parameters. Since the data were not normally distributed, we used Spearman's correlation (ρ) and we took p=0.05 as a threshold for significance.

III. Results

A. Training

After a first session of familiarization, subjects participated in a sequence of training sessions: 17, 19, 18, 19, 16, 18 for S1-S6, respectively. All the subjects started to exercise with a passive paradigm, but at the end of training five of them walked with the adaptive (active) modality. Only subject S3 was able to walk just with passive training: her WHS was the lowest and equal to three at the beginning of training. The duration of each session was limited by fatigue and depended on individual endurance. With training, 5/6 subjects improved

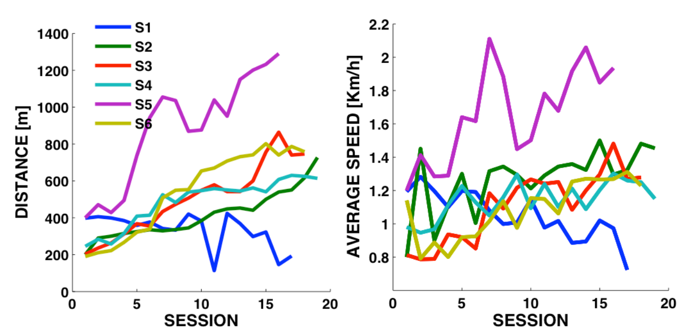

Figure 1.Time course of the gait parameter during robot-assisted training.

TABLE II. Clinical tests

	10MWT (normal speed) [m/min]			10MWT (max speed) [m/min]			6minWT [m]		TUG [s]		
	T0	T1	T2	T0	T1	T2	T0	T1	T0	T1	T2
S1	42.8±1.05	--	46±2.56	48.8±0.46	--	53±0.63	225	246	17.13	---	12.5
S2	33.1±0.18	34.1±0.66	36.4±0.95	37.6±3.53	36.5±1.21	36.2±2.71	198	218	19.5	18.1	18
S3	22.4±0.77	27.7±0.72	27.7±1.36	26±0.51	30±0.5	30.7±0.3	140	179	21	20.3	19.5
S4	25.2±0.41	31.1±1.07	30.4±4.47	31.3±0.72	35.8±2.57	38.2±1.65	148	160	32.4	26.5	21.8
S5	31.6±2.47	47.1±0.92	49.2±2.72	50.2±1.44	68.4±4.21	68.1±1.4	285	345	11.5	9.19	8.66
S6	38±1.85	40.6±1.83	41.1±1.65	51.7±1.88	50±1.8	50.2±0.4	180	227	17.5	17.5	14.5

T=time of evaluation: T0= pre- T1=middle- T2=after- training. S = subject. Mean ± standard deviation on the consecutive tests

their endurance (e.g. duration increased from 15.83±1.54SE to 31.66±3.45SE, minutes, p=0.06; SE= standard error) and increased not only the walked distance (from 272.66±40.68SE to 721.33±143.3SE meters, p=0.06), but also the walking speed (from 1.02±0.07SE to 1.29±0.16SE km/h). Figure 1 clearly shows that two subjects (S1 and S5) started from equal performance, but with training S1 worsened, while S5 improved more than all the other subjects. At the end of the training all subjects reported a subjective feeling of improvement in their ability to walk, and more specifically an increased stability and self-confidence, as well as a decrease in fatigue. S3 improved her WHS score (from 3 to 4).

B. Clinical evaluations detect a significant improvement of the walking abilities in stroke survivors.

All six chronic stroke survivors decreased significantly (p=0.03) the TUG test (from 19.8 ± 2.8 SE to 15.8 ± 2 SE seconds) and the distance walked in 6 minutes (from 196 ± 22 SE to 229.2 ± 26.5 SE meters). In the 10MWT subjects improved their normal speed (p=0.03) and 4 of them improved also their maximum speed (Table II). It is worth noting that S5, the subject who had the largest improvement during treatment, had the best performance with respect to the other subjects in all of these tests at the end of training, but not at the beginning. Instead, the score of subject S1 during the clinical tests did not show any indication of his low performance level during training.

C. Instrumented evaluation

Spatial and temporal parameter. The instrumented evaluation confirmed the results of the clinical tests i.e the self-placed mean speed increased for all subjects, as well as the speed progression of the body on the paretic foot (Table III). We found no changes in step width and double stance time parameters. Cadence, stride time, and stride length improved significantly for 5/6 subjects. A more detailed analysis showed that the swing speed increased in both sides of the body. The most significant determinant of the stride time improvement was the decreased stance time (thus, the swing time of the AL) on the foot of the not paretic limb. The latter parameter is also positively and strongly correlated with the changes in performance – walking distance - of our subjects' population between the final and initial training sessions (R=0.88 p=0.03). With respect to the other parameters we found in general a high, but not significant correlation coefficient. Specifically, the spatio-temporal parameters clearly show a greater rate of improvement for S5 with respect to the other subjects, a trend that corresponds to the one

Table III. Spatial and temporal parameters

	T0	T2	p		Affected			Unaffected		
Speed [m/s]	0.41 (0.04)	0.49 (0.05)	0.03		T0	T2	p	T0	T2	p
Cadence [steps/min]	75.17 (9.55)	80.90 (9.12)	0.09	**Step length [m]**	0.31 (0.03)	0.33 (0.03)	-	0.030 (0.03)	0.034 (0.03)	-
Stride time [s]	1.63 (0.09)	1.50 (0.07)	0.09	**Swing speed [m/s]**	0.94 (0.09)	1.13 (0.09)	0.03	1.32 (0.14)	1.58 (0.15)	0.06
Stride length [m]	0.65 (0.06)	0.73 (0.05)	0.06	**Swing time [s]**	0.65 (0.04)	0.57 (0.04)	0.09	0.41 (0.04)	0.39 (0.02)	-
Step width [m]	0.22 (0.01)	0.22 (0.01)	-	**Double stance time [s]**	0.28 (0.03)	0.25 (0.03)	-	0.28 (0.02)	0.27 (0.02)	-
Speed Progression on the paretic foot [m/s]	0.41 (0.05)	0.49 (0.06)	0.03	**Stance time [s]**	0.98 (0.07)	0.92 (0.07)	-	1.2 (0.06)	1.12 (0.07)	0.09

Mean (Standard Error, SE). Affected and unaffected side of the body. T0 pre treatment and T2 post treatment evaluation.

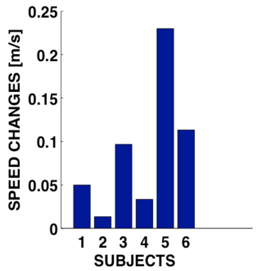

Figure 2. Variation of the walking speed between before and after training.

observed during training. The performance improvement of S5, indeed, was significantly above the average values of the other subjects (Figure 2). Normalizing to 1 the average improvement value for each variable, we have for S5: speed 2.57, speed progression over the paretic foot 2.52, stride length 3.13, stride time 1.46, swing speed and time on the paretic side respectively 2.88 and 2.22, swing speed and time on the not paretic side respectively 1.62 and 1.33, time of stance not paretic side 1.89. However, as for the clinical tests, the temporal and spatial parameters - do not provide any indication correlated with the worsening in training performance of S1.

Kinematic parameters

Sagittal plane. *Pelvis.* 5/6 subjects (except S6) in the pre-training evaluation have an antiversion of the pelvis. After training the antiversion was significantly reduced for all subjects (p=0.03) from an average value of 12.66±3.67 SE to 7.82±3.17 SE degrees. This change was significant (p=0.03) also when subjects maintained a quiet standing posture (from 9.1±2.8 SE to 3.8± 1.8 SE).

Hip. The most significant modifications at the level of the hip joint are the extension in the final stance (minimum) phase and the flexion (maximum) at the end of the middle of swing phase. With respect to the former parameter, 4/6 subjects on the AL (from -2.1±4.3 SE to -8.4 ±5.1 SE deg) and 5/6 on the NL (from -3.59±5.43 SE to -11.9±6.4 SE deg, p=0.09) increased their degrees of hip extension. With respect to the latter parameter, no significant trend was found on the AL while in the NL 5/6 subjects (except S1) slightly decreased (p=0.06) their maximum value in flexion (from 36.8±4.7 SE to 30.6±5.3 SE deg). S1, instead, increased his dominant hip flexion pattern: the flexion in the not paretic side was greater than the normal values before training and it further increased after treatment. This resulted also in an inability to extend the hip in the terminal stance phase, parameter that worsened in both limbs after training (Figure 3 bottom panel).

Knee. The knee flexion during walking has a minimum at the end of middle stance phase (about 3 deg.) and a maximum during the swing phase (about 60 deg.). We focused the analysis on these two relevant points. The results we obtained confirm what is suggested by mechanical constraints: the extension of the hip joint controls the flexion movements of the knee joint during standing and stance-phase of walking.

In the AL, no significant trend was found in the subject group. However, S1 reduced the hyperextension in the midstance of about 10 degrees, achieving a value that post training was closer to normal (AL: from -10.3 to -1.7 deg) values. With respect to the NL, while most subjects -5/6- slightly decreased (from 4.4 ±41 SE to 1± 4.8 SE deg) the minimum knee flexion during stance, S1 had an opposite trend (figure 3) increasing of 18 degrees the knee flexion, thus maintaining this flexion pattern during the middle and the terminal stance phases. S1 increased also the flexion peak in the middle swing

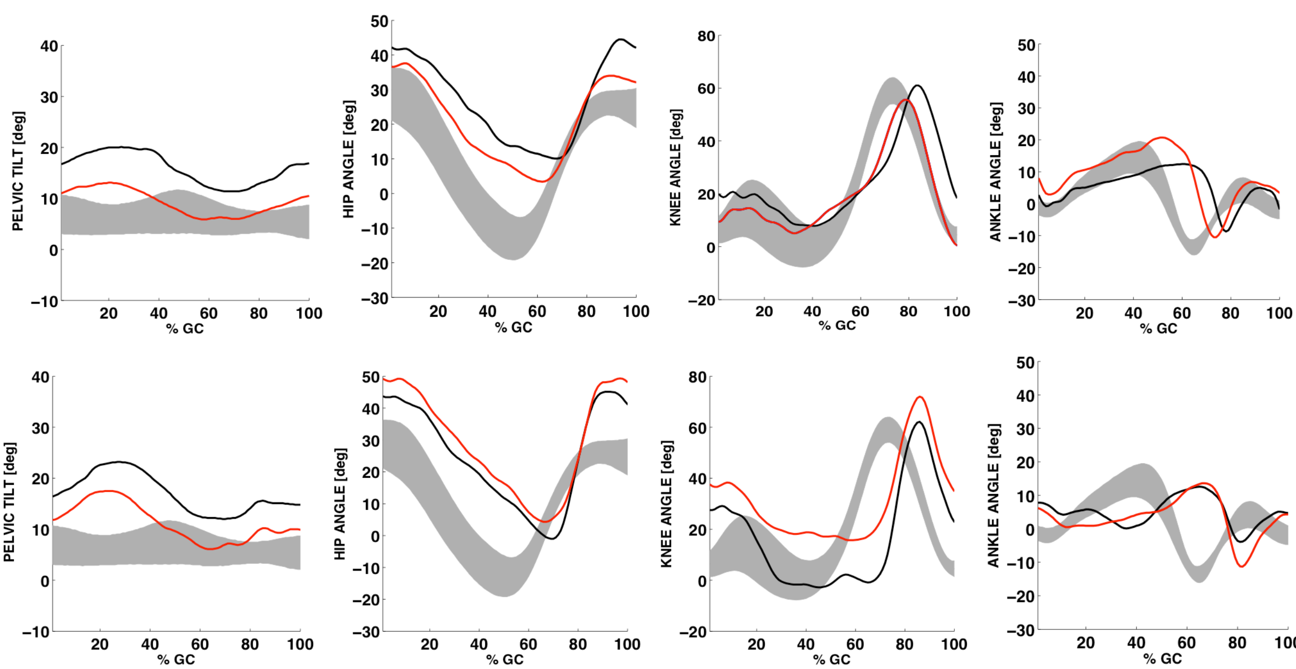

Figure 3. Sagittal plane. Angle of the joint of the limb ipsilateral to the lesion for subject S5 (top panel) and S1 (bottom panel). GC=gait cycle. Data are referred to a single gait cycle. Gray shadow: Normality range mean±std. Black line: performance before treatment. Red: performance after treatment. Positive and negative angle values are referred respectively to flexion and extension.

phase in both limbs (AL: from 4.9 to 11.6 deg, NL: from 61.8 to 72.2 deg). This is a positive result for the paretic limb that improved his flexion during swing, while it is negative in the NL where flexion exceeded the normality values.

Ankle. The range of dorsiflexion of the ankle increased for 5/6 subjects (p=0.09) on the not affected side (from 20.5 ± 1 SE to 23.6 ±1.4 SE degrees). The changes are due to an improved ability to plantiflexion (from -4.7±1.8 SE to -8.6±1.8 SE) during the preswing phase (p=0.03), preparing the conditions for a better dorsiflexion.

Frontal plane and Transverse plane

We did not find – and did not expect - any remarkable trend in the frontal (adbduction-adduction) and transverse planes (intra-extra rotation), except a slight but significant (p=0.09) decrease of the range and in the maximum (absolute value) of inclination of the pelvis from 6.18±0.96 SE to 5.22±0.73 SE deg and from 9.1±0.81 SE to 8.2±1.16 SE deg., respectively.

IV. DISCUSSION

The first qualitative result is that all the subjects were satisfied with respect to the protocol of robot-assisted gait re-education, even the subject with the lowest performance level. Their subjective feeling of increased self-confidence was confirmed by the improved self-paced walking speed in both the clinical and instrumented tests. Moreover, improved stability is supported by the decrease of pelvis antiversion that modifies the subjects' standing posture. This change determines an orientation of the ground reaction force vector that is closer to normal, thus increasing balance both during standing and walking. The improvement in the walking speed is related to both the length and the time of the stride. As a consequence of increased stability, we could expect also a decrease of the step width, but this did not occur. We wonder if this could be related to the fact that the distance between the two feet in the robot is fixed. Other important aspects that were not modified by the robot training protocol are the kinematic variables in the transverse plane that provide important information on the progression of the body in space. This may be correlated with the fact that the design of the robot does not allow a real progression in the transverse plane, namely the subjects' walk without moving forward. We cannot drive solid conclusions on such matters because of the small sample size of our subject population, but the problem was already reported for the exoskeleton robots [30].

We found interesting the results related to the influence of gait training on the non-affected leg, thus on the better quality of compensatory strategies. After a stroke, also the side ispilateral to the lesion is thought to be "affected" in a different, but equally severe way as the contralateral side: spatiotemporal, kinetic, and kinematic variables are indeed far from normal in both sides. Our study suggests indeed that robot training modifies spatio-temporal as well as kinematic patterns of both affected and non-affected sides and the overall trend is in quite positive. This implies that in our population of subjects the non-affected side becomes less involved in attempting to compensate for the deficiencies of the affected side, thus reducing the importance of compensation strategies.

This work also highlights the fact that instrumented gait analysis can provide important insight on our understanding of the individual subject's performance gains related to training. Specifically, in this study we had two subjects that started the training with almost equal performance, but while one had the best rate of improvement of our subject population, the other slightly worsened his performance level. The clinical test and the spatio-temporal parameter succeeded in reporting a greater improvement of the first subject with respect to the other, although he did not have a performance level worse than the average. The analysis of the kinematic variables allowed us to clarify the origin of the problem: this subject did exhibit an improvement of the affected limb indicators, as all the other subjects, but he also increased his compensatory strategies; more specifically, he increased his dominant flexion pattern at the level of the hip and knee joints in the side ipsilateral to the lesion. This mechanism does not correspond to a "true recovery" [13]. The gait analysis allowed us to detect the problem at its beginning and it was immediately corrected by the rehabilitation team. At the follow up, the compensatory mechanism was again reduced to the before trainings levels. Surely we cannot speculate on a single subject, however we can highlight the fact that in an endpoint robot as the G-EO the movement of the hip and the knee joints are not controlled. The use of an exoskeleton robot that constrains the joint movements is not the solution of this problem: some studies reported that exoskeleton-based systems for gait rehab forced patients to perform compensatory movements, resulting in altered muscle activation patterns [31, 32]. Therefore, the correct solution is the integration of the work of the robot with the one of the physical therapist, that can guaranties the correct use of the robot itself and maximizing its efficacy. Finally, we found interesting that the subject who had a behavior different from the population trend was the only one with the lesion in the right hemisphere and thus could be affected by some degree of misperception often found in subjects with left hemiparesis [33]. Our future work we will be focus on completing the analysis with kinetic data, augmenting the population of the study with a more balanced enrollment of left and right hemiparesis, and investigating specifically (a) the effect of robot assisted gait training on compensatory strategies and on the "not affected" limb; (b) the difference in recovery induced by robot assisted gait rehabilitation for subject with left and right hemisphere lesions (c) the comparison of the outcomes of endpoint and exoskeleton based robots.

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REFERENCES

[1] V. L. Feigin, C. M. Lawes, D. A. Bennett, S. L. Barker-Collo, and V. Parag, "Worldwide stroke incidence and early case fatality reported in 56 population-based studies: a systematic review," *Lancet Neurol,* vol. 8, pp. 355-69, Apr 2009.

[2] H. Nakayama, H. S. Jorgensen, H. O. Raaschou, and T. S. Olsen, "Recovery Of Upper Extremity Function In Stroke Patients - The Copenhagen Stroke Study," *Archives of physical medicine and rehabilitation,* vol. 75, pp. 394-398, Apr 1994.

[3] J. W. Lance, "The control of muscle tone, reflexes, and movement: Robert Wartenberg Lecture," *Neurology,* vol. 30, pp. 1303-13, Dec 1980.

[4] D. Burke, "Spasticity as an adaptation to pyramidal tract injury," *Adv Neurol,* vol. 47, pp. 401-23, 1988.

[5] T. E. Twitchell, "The restoration of motor function following hemiplegia in man," *Brain,* vol. 74, pp. 443-80, Dec 1951.

[6] S. Brunnstrom, *Movement Therapy in Hemiplegia: A Neuropsychological Approach*. New York: Harper and Row, 1970.

[7] D. Bourbonnais and S. Vanden Noven, "Weakness in patients with hemiparesis," *Am J Occup Ther,* vol. 43, pp. 313-9, May 1989.

[8] P. Archambault, P. Pigeon, A. G. Feldman, and M. F. Levin, "Recruitment and sequencing of different degrees of freedom during pointing movements involving the trunk in healthy and hemiparetic subjects," *Exp Brain Res,* vol. 126, pp. 55-67, May 1999.

[9] T. N. Levin, T. Feldman, and J. D. Carroll, "Effect of atrial septal occlusion on mitral area after Inoue balloon valvotomy," *Cathet Cardiovasc Diagn,* vol. 33, pp. 308-14, Dec 1994.

[10] M. F. Levin and M. Dimov, "Spatial zones for muscle coactivation and the control of postural stability," *Brain Res,* vol. 757, pp. 43-59, May 16 1997.

[11] M. F. Levin, "Interjoint coordination during pointing movements is disrupted in spastic hemiparesis," *Brain,* vol. 119 (Pt 1), pp. 281-93, Feb 1996.

[12] S. F. Tyson, M. Hanley, J. Chillala, A. B. Selley, and R. C. Tallis, "Sensory loss in hospital-admitted people with stroke: characteristics, associated factors, and relationship with function," *Neurorehabil Neural Repair,* vol. 22, pp. 166-72, Mar-Apr 2008.

[13] M. F. Levin, "Should stereotypic movement synergies in hemiparetic patients be considered adaptive?," *Behavioral and Brain Sciences,* vol. 19, pp. 79-&, Mar 1996.

[14] A. Pennycott, D. Wyss, H. Vallery, V. Klamroth-Marganska, and R. Riener, "Towards more effective robotic gait training for stroke rehabilitation: a review," *J Neuroeng Rehabil,* vol. 9, p. 65, 2012.

[15] P. Sale, M. Franceschini, A. Waldner, and S. Hesse, "Use of the robot assisted gait therapy in rehabilitation of patients with stroke and spinal cord injury," *Eur J Phys Rehabil Med,* vol. 48, pp. 111-21, Mar 2012.

[16] J. Mehrholz, C. Werner, J. Kugler, and M. Pohl, "Electromechanical-assisted training for walking after stroke," *Cochrane Database Syst Rev,* p. CD006185, 2007.

[17] S. Fisher, L. Lucas, and T. A. Thrasher, "Robot-assisted gait training for patients with hemiparesis due to stroke," *Top Stroke Rehabil,* vol. 18, pp. 269-76, May-Jun 2011.

[18] C. Geroin, A. Picelli, D. Munari, A. Waldner, C. Tomelleri, and N. Smania, "Combined transcranial direct current stimulation and robot-assisted gait training in patients with chronic stroke: a preliminary comparison," *Clin Rehabil,* vol. 25, pp. 537-48, Jun 2011.

[19] G. Kwakkel, B. J. Kollen, and H. I. Krebs, "Effects of Robot-Assisted Therapy on Upper Limb Recovery After Stroke: A Systematic Review," *Neurorehabil Neural Repair,* Sep 17 2007.

[20] S. Hesse, A. Waldner, and C. Tomelleri, "Innovative gait robot for the repetitive practice of floor walking and stair climbing up and down in stroke patients," *J Neuroeng Rehabil,* vol. 7, p. 30, 2010.

[21] M. F. Folstein, S. E. Folstein, and P. R. McHugh, ""Mini-mental state". A practical method for grading the cognitive state of patients for the clinician," *J Psychiatr Res,* vol. 12, pp. 189-98, Nov 1975.

[22] J. Perry, M. Garrett, J. K. Gronley, and S. J. Mulroy, "Classification of walking handicap in the stroke population," *Stroke,* vol. 26, pp. 982-9, Jun 1995.

[23] D. T. Wade, V. A. Wood, A. Heller, J. Maggs, and R. Langton Hewer, "Walking after stroke. Measurement and recovery over the first 3 months," *Scand J Rehabil Med,* vol. 19, pp. 25-30, 1987.

[24] M. Kosak and T. Smith, "Comparison of the 2-, 6-, and 12-minute walk tests in patients with stroke," *J Rehabil Res Dev,* vol. 42, pp. 103-7, Jan-Feb 2005.

[25] D. Podsiadlo and S. Richardson, "The timed "Up & Go": a test of basic functional mobility for frail elderly persons," *J Am Geriatr Soc,* vol. 39, pp. 142-8, Feb 1991.

[26] R. B. Davis, "Clinical gait analysis," *IEEE Eng Med Biol Mag,* vol. 7, pp. 35-40, 1988.

[27] S. Carda, M. Bertoni, P. Zerbinati, M. Rossini, L. Magoni, and F. Molteni, "Gait changes after tendon functional surgery for equinovarus foot in patients with stroke: assessment of temporo-spatial, kinetic, and kinematic parameters in 177 patients," *Am J Phys Med Rehabil,* vol. 88, pp. 292-301, Apr 2009.

[28] F. Wilcoxon, "Individual comparisons of grouped data by ranking methods," *J Econ Entomol,* vol. 39, p. 269, Apr 1946.

[29] G. Chen, C. Patten, D. H. Kothari, and F. E. Zajac, "Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds," *Gait Posture,* vol. 22, pp. 51-6, Aug 2005.

[30] J. F. Veneman, J. Menger, E. H. van Asseldonk, F. C. van der Helm, and H. van der Kooij, "Fixating the pelvis in the horizontal plane affects gait characteristics," *Gait Posture,* vol. 28, pp. 157-63, Jul 2008.

[31] J. F. Israel, D. D. Campbell, J. H. Kahn, and T. G. Hornby, "Metabolic costs and muscle activity patterns during robotic- and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury," *Phys Ther,* vol. 86, pp. 1466-78, Nov 2006.

[32] J. M. Hidler and A. E. Wall, "Alterations in muscle activation patterns during robotic-assisted walking," *Clin Biomech (Bristol, Avon),* vol. 20, pp. 184-93, Feb 2005.

[33] C. Lafosse, E. Kerckhofs, M. Troch, P. Santens, and E. Vandenbussche, "Graviceptive misperception of the postural vertical after right hemisphere damage," *Neuroreport,* vol. 15, pp. 887-91, Apr 9 2004.