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Assessing Stiffness, Joint Torque and ROM for Paretic and Non-Paretic Lower Limbs during the Subacute Phase of Stroke Using Lokomat Tools

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Abstract: The efficacy of Lokomat on motor recovery in stroke patients is well known. However, few studies have examined Lokomat tools to assess stiffness, joint torque and range of motion (ROM) during the subacute phase of stroke. The purpose of this retrospective observational study is to assess the changes of joint torque, ROM and stiffness that were estimated with Lokomat tools, namely L-FORCE (lower limb-force), L-ROM (lower limb-range of motion)and L-STIFF (lower limb-stiff), for paretic and non-paretic lower limbs in the subacute phase of stroke, assuming that the tools were able to measure these changes. The data come from 10 subjects in the subacute phase who had their first ever-stroke and followed a treatment that included Lokomat. The measurements came from basal assessments (T0) and one-month follow-up (T1). The measures were compared between paretic and non-paretic legs, and between T0 and T1. Significant differences in stiffness, joint torque and ROM were obtained between the paretic and non-paretic limbs at both T0 and T1. A non-significant trend was obtained for reduced stiffness and increased torque and ROM between T0 and T1 of the paretic limbs. The Lokomat tools were able to measure the changes between paretic and non-paretic legs and the small changes between T0 and T1 measurements.

Keywords: biomechanics; neurorehabilitation; stroke; Lokomat; stiffness; joint torque; range of motion (ROM)

1. Introduction

The stroke is a dramatic vascular event that causes death in 20% of cases and chronic disability in most survivors [1]. Spastic hemiparesis is one of the most disabling consequences of a stroke. Muscle weakness due to disruption of corticospinal pathways occurs immediately [2], while spasticity appears later as a result of plastic neuronal changes within the central nervous system after the initial injury [3].

Weakness and spasticity are essential diagnostic and prognostic elements for delineating effective rehabilitation strategies. The most commonly used techniques for measuring strength in clinical practices are the Medical Research Council (MRC) scale and the hand-held dynamometer (HHD). These techniques have limitations, since they are semi-subjective and not able to guarantee an isometric contraction respectively; moreover, the lying or sitting postures used during these tests do not correspond to the walking posture [4,5].

The Modified Ashworth Scale (MAS) and the Modified Tardieu Scale (MTS) are the most widely utilized instruments to estimate spasticity. Their application is limited by the operator's experience and the difficulty of controlling the movement's speed during the test [6,7].

Isokinetic dynamometry represents a quantitative approach for measuring strength. However, its use is not yet widespread due to high cost [8,9].

Lokomat (Hocoma, Volketswil, Switzerland) is the most frequently used walking robotic aid in rehabilitation [10]. This aid supports the weight of patients and assists hip and knee effort by means of four servomotors. L-FORCE (lower limb-force) [11,12] is a Lokomat tool that measures torque at the hip and the knee joints during maximal voluntary isometric torque. L-STIFF (lower limb-stiff) [12,13] is a Lokomat tool that measures how resistive torque changes in the hip and knee during both flexion and extension for predefined passive movements, by moving the joint at a constant velocity. L-ROM (lower limb-range of motion) [12] is a Lokomat tool that measures the passive range of motion (ROM) of the hip and knee without support of the Lokomat drives. Therefore, L-FORCE, L-STIFF and L-ROM allow follow-up of joint torque, stiffness and joint range of motion during a Lokomat training session, respectively [10]. Since weakness and spasticity are directly related to joint torque and stiffness, Lokomat can be considered a suitable measurement tool for weakness and spasticity estimation in rehabilitation processes.

The efficacy of Lokomat on motor recovery in patients suffering stroke is well known [14,15]. Regarding L-FORCE, L-STIFF and L-ROM tools of Lokomat, they have been addressed in different studies. Particularly, in studies related to children with cerebral palsy. In [16] the authors found that L-STIFF is a feasible tool to assess the stiffness in children with cerebral palsy. Likewise, in [13] the authors found that the L-STIFF is a promising tool to assess spasticity in children with cerebral palsy in a standing position. Regarding subacute stroke, some works have addressed the effectiveness of the Lokomat such as the studies in [17–19]. However, in [17–19], L-FORCE, L-STIFF and L-ROM tools were not addressed for subacute stroke. Therefore, a study related to joint torque, stiffness, and joint ROM obtained using L-FORCE, L-STIFF and L-ROM tools of Lokomat, particularly in the subacute phase of stroke, is interesting. The purpose of this retrospective observational study is to assess the changes of joint torque, ROM, and stiffness that were estimated with Lokomat tools, namely L-FORCE, L-ROM and L-STIFF, for paretic and non-paretic lower limbs in the subacute phase of stroke, assuming that the tools were able to measure these changes. Data obtained using L-Force, L-Stiff and L-ROM tools for stroke patients in subacute phase were compared between paretic and non-paretic sides before and after a rehabilitation treatment with Lokomat.

2. Materials and Methods

2.1. Design of the Study

This is a retrospective observational study where data were used from clinical outcomes of 10 patients who had their first-ever stroke and who underwent to treatment program that included gait training with Lokomat, as part of their rehabilitative routine procedures. The patients had been diagnosed and treated at IRCCS NEUROMED—the Mediterranean Neurological Institute (Italy), according to the national guidelines and agreements that govern its hospital center. All data were collected as part of routine diagnosis and treatment. Every day IRCCS NEUROMED offers therapies at the highest level, accompanied by assistance always attentive to the needs of patients, using the latest technology in rehabilitation such as the Lokomat pro V6. At the beginning and at the end of the Lokomat training the therapists routinely measures the stiffness, the joint torque and the ROM using dedicated Lokomat tools as clinical instrument to monitor patient improvements and the clinical outcomes are recorded in the medical file of patients. This study looked retrospectively at clinical outcomes from patients who met an inclusion criteria, finding 5 patients among clinical outcomes collected in 2017 and 5 patients among clinical outcomes collected in 2018. Patients entering IRCCS NEUROMED gave a generic consent to use their data for future scientific research purposes according to GDPR (General Data Protection Regulation) regulation. This study does not report on the use of experimental or new protocols. Although the rehabilitation program carried out by the 10 selected patients is described in this study, the rehabilitation program was neither designed nor modified for the purposes of this study.

2.2. Participants

The data used in this study come from 10 subjects (8 men and 2 women), with a mean (standard deviation, SD) age of 60.4 (12.31) years. Five of them had suffered from an ischemic stroke, while the others had suffered from a hemorrhagic stroke. Eight patients had a right hemiparesis, while two had a left one. Clinical and demographic characteristics are summarized in Table 1.

Table 1. Clinical and demographic of the subjects included in the study.

ID [2]	Sex	Age (Yrs. [3])	Days Since Stroke	FAC [1]		Etiology and Imagines	Clinical Pictures
				At Basal Assessments (T0)	At One-Month Follow-Up (T1)		
1	M [4]	43	10	1	4	Left temporo insular ischemia	Right hemiparesis and aphasia
2	M	60	13	1	4	Right thalamo capsular haemorragia	Left hemiparesis
3	M	77	52	1	5	Right thalamo capsular haemorragia	Left hemiparesis
4	M	63	12	3	6	Left corona radiata ischemia	Right hemiparesis
5	M	70	23	1	2	Left corona radiata ischemia	Right hemiparesis
6	M	36	47	1	1	Left thalamo capsular haemorragia	Right hemiparesis and aphasia
7	M	54	51	1	2	Left parieto occipital haemorragia	Right hemiparesis and aphasia
8	F [5]	73	15	1	3	Left parieto occipital haemorragia	Right hemiparesis
9	M	61	60	3	6	Left corona radiata ischemia	Right hemiparesis
10	F	67	16	1	3	Left corona radiata ischemia	Right hemiparesis and aphasia

[1] FAC = functional ambulation classification. [2] ID = Identification number. [3] Yrs. = Years. [4] M = Male. [5] F = Female.

Inclusion criteria were: (1) hemiparesis due to an ischemic or hemorrhagic stroke; (2) time since stroke onset <2 months; (3) ability to understand and follow instructions related to the experiment; (4) functional ambulation classification (FAC) category ≥1 [20].

Exclusion criteria were: (1) history of multiple strokes; (2) bilateral involvement; (3) stiffness limiting the full ROM of the impaired side; (4) presence of neglect or global aphasia; (5) use of spasticity treatments, inclusive of previous botulinum toxin injections.

Stroke was diagnosed by neurologists with expertise in a Stroke Unit, and according to international guidelines.

2.3. Rehabilitative Program

The data were collected from patients that were part of a subacute intensive rehabilitative program, lasting about four consecutive weeks in relation to body impairment and dysfunction. It included physiotherapy, speech therapy, occupational therapy, and neuropsychological therapy.

As part of their rehabilitation program, the patients who were able to walk according to FAC category 1, that is, who required assistance from no more than one person during gait, participated in four weeks of daily 30 min flat training sessions with Lokomat Pro V6. The treadmill speed for all participants was 1.5 km/h with 50% body weight support. The body weight support was provided using a suspended harness available in Lokomat Pro V6 and it was adjusted to support 50% of the patient' body weight. The guidance force parameter was set to 100%. The stiffness, joint torque and range of motion was assessed for each patient at admission and 4 weeks after using the Lokomat tools: L-STIFF, L-FORCE and L-ROM. The measurement protocol is detailed in Section 2.4.

In the rehabilitative program the 30 min training sessions were carried out using Lokomat Pro V6 (Hocoma, Volketswil, Switzerland). Lokomat Pro V6 is a driven gait orthosis with transducers and electrical drives in hip and knee joints for automatic locomotion therapy [21]. Using Lokomat Pro V6, the therapist can control the robot via computer while an electronic display is available for the patients. The treadmill of Lokomat Pro V6 works within a speed range from 0 to 10 km/h and it can be adjusted for each patient. Measurement tools are available in Lokomat Pro V6 such as L-STIFF, L-FORCE and L-ROM. The L-STIFF, L-FORCE and L-ROM tools were described in the introduction. Detailed technical data of Lokomat Pro V6 can be obtained in [21].

2.4. Measurement Protocol

Joint torque was assessed bilaterally in hip and knee flexors and extensors using the L-FORCE tool [11,12]. Tests were performed by an experienced therapist (PN). Each patient was installed in Lokomat, with pre-set fixed joints angles (20° hip flexion with respect to the longitudinal axis of the body and 20° knee flexion with respect to the femur axis). During the test, the instruction "3-2-1-go" was displayed on a computer screen, and was verbally given by the tester. All patients were instructed to produce as much force as fast as possible, and were required to hold the maximum force for 4 sec. Joint torque was measured by Lokomat, and was displayed on the screen for the patient and tester. Maximum hip and knee flexion were reported, along with extension torque.

Hip and knee stiffness were assessed by the L-STIFF tool [12,13]. The patients were lifted above the treadmill (unloading 100% of their body weight), allowing them to move hip and knee joints freely without touching the ground with their feet. Then, Lokomat performed the controlled displacement of left and right hips and knees in flexion and extension at three angular velocities (22.50°/s, 45°/s, and 90°/s for the hip and 30°/s, 60°/s, and 120°/s for the knee).

The passive range of motion of hip and knee for each patient were assessed using the L-ROM tool. The L-ROM tool measures the passive range of motion without support of the Lokomat drives [12].

This measurement protocol is part of the routine procedures to monitor the patient's improvement using Lokomat and the data are typically recorded in the medical file of patients. Since the measurement protocol is a routine procedure that was not designed or modified for the purposes of this study, the therapist took only one measure; meanwhile, Lokomat was assumed as a reliable clinical instrument for rehabilitation purposes. The measures assessed for each subject using L-FORCE and L-ROM tools, at basal assessments (T0) and at one-month follow-up (T1), were obtained using one trial. The measures assessed for each subject using L-STIFF tool, at T0 and at T1 for the three angular velocities, were obtained using three trials given that L-STIFF tool of Lokomat Pro V6 automatically performs three trials and delivers the median value to the therapist.

2.5. Statistical Analysis

The mean and SD of each dataset were computed. Therefore, a mean value and a SD value were calculated for the L-FORCE measures obtained from the 10 subjects at basal assessments (T0) and for the L-FORCE measures at one-month follow-up (T1). Similarly, a mean value and a SD value were calculated for the L-STIFF measures from the 10 subjects, at T0 and at T1, for each used angular velocity. Likewise, a mean value and an SD value were calculated for the L-ROM measures from the 10 subjects at T0 and at T1. The Wilcoxon signed-rank test was used to estimate the significance of the differences between measures of paretic and non-paretic legs and between measures at basal assessments (T0) and at one-month follow-up (T1). Since sample size impacts significantly on sample distribution and small sample sizes are often observed to result in non-normal distribution [22], it is difficult to check whether a small size dataset is really normally distributed or not normally distributed. Therefore, the chosen technique was a non-parametric method, which did not need any specific distribution of probability. However, a rapid test was carried out to check the distribution of the dataset using lillietest function in Matlab 2017b (MathWorks Inc., Natick, 226 MA, USA). The lilliestest function gives back a test decision for the null hypothesis that the evaluated data vector comes from a distribution in the normal

family [23]. Detailed information about lillietest function can be found in [23]. In this case, the lillietest function indicated that the dataset of this study exhibits both non-normally distributed and normally distributed data (using a 5% significance level). Therefore, the lilliestest results confirmed that a non-parametric method continues to be more appropriate for this study. In particular, the Wilcoxon signed-rank test is very suitable for a repeated measures design where the same subjects are evaluated under two different conditions [24] such as the measures design in this study. Wilcoxon Signed-Rank Test has been applied using the signrank function in Matlab 2017b (MathWorks Inc., Natick, 226 MA, USA). The signrank function returns the *p*-value of a paired, two-sided test for the null hypothesis that the compared data come from a distribution with zero median. All differences were considered statistically significant at $p < 0.05$. Detailed information about signrank function can be found in [25].

3. Results

3.1. Stiffness

Table 2 shows the mean of the L-STIFF measures (stiffness assessment) for the paretic and non-paretic lower limbs at basal assessments (T0) and at one-month follow-up (T1). In addition, Table 2 presents the significance values (*p*-value) estimated using the Wilcoxon signed-rank test by comparing the L-STIFF values obtained for the paretic and the non-paretic legs, at T0 and T1, as detailed in the footers of the same table (Table 2). Figure 1 shows a plot of the mean measures obtained for paretic and non-paretic limb at T0 and at T1.

Table 2. Mean and standard deviation (SD) of the L-STIFF measures (Nm/°) for paretic and non-paretic limbs at basal assessments (T0) and one-month follow-up (T1).

		L-STIFF ** (Nm/°)								*p*-Value *			
		For Paretic Legs				For Non-paretic Legs							
		At T0		At T1		At T0		At T1		*P*1 [1]	*P*2 [2]	*P*3 [3]	*P*4 [4]
	Angular Velocity	Mean	SD	Mean	SD	Mean	SD	Mean	SD				
Hip Ext. [5]	22.50°/s	0.67	±0.26	0.57	±0.14	0.47	±0.20	0.45	±0.19	<0.05	ns	ns	ns
	45°/s	0.67	±0.27	0.61	±0.17	0.48	±0.17	0.49	±0.11	<0.01	<0.05	ns	ns
	90°/s	0.70	±0.27	0.66	±0.17	0.56	±0.22	0.54	±0.12	<0.05	ns	ns	ns
Hip Flex. [6]	22.50°/s	0.62	±0.26	0.56	±0.13	0.46	±0.19	0.43	±0.19	<0.05	<0.05	ns	ns
	45°/s	0.60	±0.25	0.58	±0.18	0.41	±0.18	0.43	±0.11	<0.01	<0.05	ns	ns
	90°/s	0.66	±0.25	0.63	±0.16	0.49	±0.19	0.51	±0.14	<0.01	<0.05	ns	ns
Knee Ext.	30°/s	0.30	±0.23	0.27	±0.12	0.20	±0.20	0.18	±0.10	<0.05	<0.05	ns	ns
	60°/s	0.31	±0.24	0.25	±0.12	0.19	±0.18	0.18	±0.10	<0.01	<0.05	ns	ns
	120°/s	0.33	±0.24	0.30	±0.11	0.21	±0.17	0.22	±0.10	<0.01	<0.05	ns	ns
Knee Flex.	30°/s	0.30	±0.24	0.29	±0.17	0.21	±0.23	0.19	±0.11	ns	<0.05	ns	ns
	60°/s	0.32	±0.23	0.27	±0.13	0.20	±0.20	0.19	±0.12	<0.05	<0.05	ns	ns
	120°/s	0.34	±0.23	0.33	±0.14	0.23	±0.19	0.24	±0.10	<0.05	<0.01	ns	ns

* *p*-value obtained using Wilcoxon signed-rank test; statistically significant at $p < 0.05$; ns = non-significant. ** L-STIFF = Lower limb-stiff. [1] *P*1 = *p*-value comparing L-STIFF at basal assessments (T0) between paretic legs and non-paretic legs. [2] *P*2 = *p*-value comparing L-STIFF at one-month follow-up (T1) between paretic legs and non-paretic legs. [3] *P*3 = *p*-value comparing L-STIFF of paretic legs at T0 and T1. [4] *P*4 = *p*-value comparing L-STIFF of non-paretic legs at T0 and T1. [5] Ext. = Extension. [6] Flex. = Flexion.

According to results in Table 2 and Figure 1, the stiffness values of the paretic legs were greater than those of non-paretic legs during the basal assessments (T0) and these stiffness differences were statistically significant ($p < 0.05$); except for knee flexion at an angular velocity of 30°/s that showed non-significant stiffness differences. Analogous results were observed at one-month follow-up (T1) where the stiffness values of the paretic legs were greater than those of non-paretic legs and these stiffness differences were statistically significant ($p < 0.05$); except for hip extension at 22.50°/s and at 90°/s that showed non-significant stiffness differences. The stiffness values of the paretic legs at one-month follow-up (T1) were lower than those at basal assessment (T0) but this decrease was not statistically significant. The stiffness values of the non-paretic legs at one-month follow-up (T1) were lower than those at basal assessment (T0) for hip extension at 22.50°/s and 90°/s, hip flexion at 22.50°/s,

knee extension at 30°/s and 60°/s, and knee flexion at 30°/s and 60°/s and the stiffness values were greater for hip extension at 45°/s, for hip flexion at 45°/s and 90°/s, knee extension at 120°/s, and knee flexion at 120°/s but these value differences were not statistically significant.

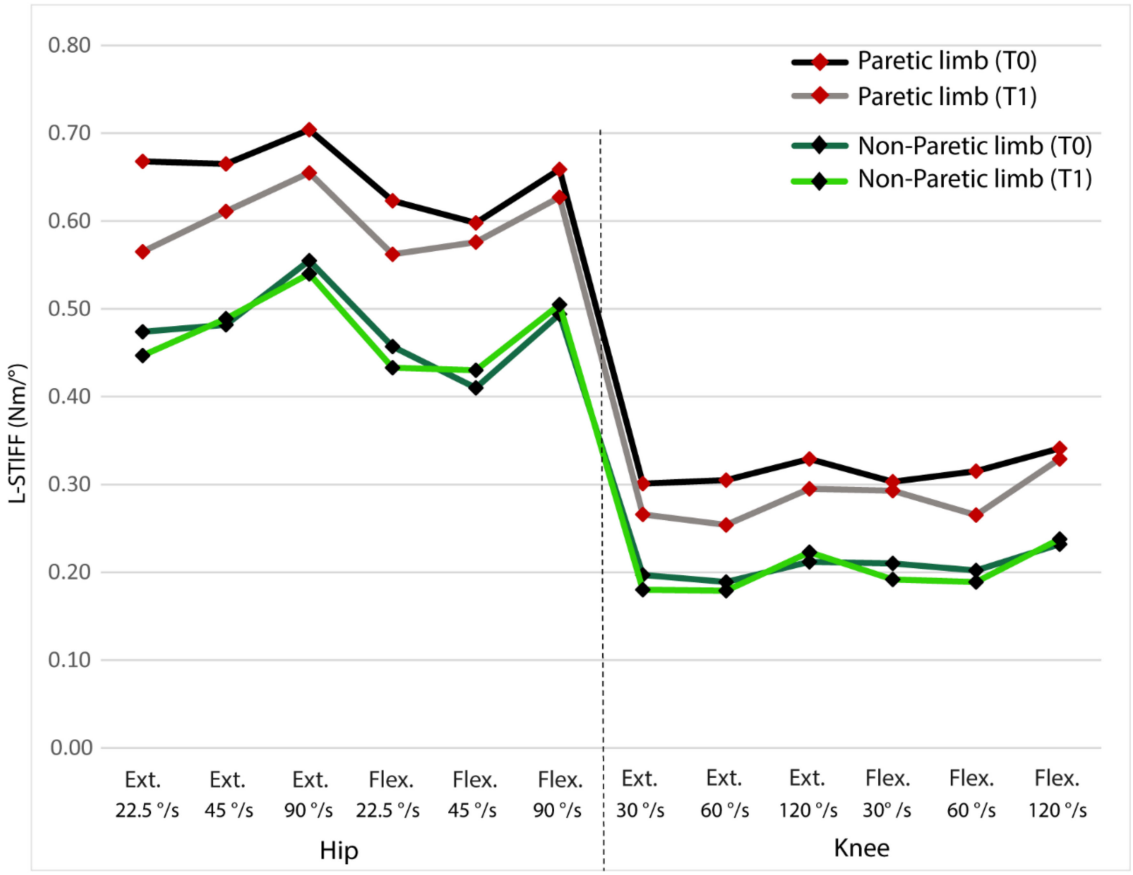

Figure 1. L-STIFF (lower limb-stiff) measures (mean) of paretic and non-paretic limb at basal assessments (T0) and one-month follow-up (T1).

3.2. Joint Torque

Table 3 shows the mean of the L-FORCE measures (joint torque assessment) for the paretic and non-paretic lower limb at basal assessments (T0) and at one-month follow-up (T1). In addition, Table 3 presents the significance values (p-value) estimated using the Wilcoxon signed-rank test by comparing the L-FORCE values obtained for the paretic and the non-paretic legs, at T0 and T1, as detailed in the footers of the same table (Table 3). Figure 2 shows a plot of the mean measures of the L-FORCE obtained for paretic and non-paretic limbs at T0 and at T1.

According to the results in Table 3 and Figure 2, the joint torque values of the paretic legs were lower than those of non-paretic legs during the basal assessments (T0) and these joint torque differences were statistically significant ($p < 0.05$). Analogous results were observed at one-month follow-up (T1) where the joint torque values of the paretic legs continued to be lower than those of non-paretic legs and these joint torque differences were statistically significant ($p < 0.05$) except for hip flexion. The joint torque values of the paretic legs at one-month follow-up (T1) were greater than those at basal assessment (T0) but this decrease was not statistically significant except for hip flexion where $p < 0.05$. The joint torque values of the non-paretic legs at one-month follow-up (T1) were greater than those at basal assessment (T0) for hip extension and knee flexion and they were lower than those at basal assessment for hip flexion and knee extension but these joint torque differences were not statistically significant.

Table 3. Mean and standard deviation (SD) of the L-FORCE measures (Nm) for paretic and non-paretic limbs at basal assessments (T0) and one-month follow-up (T1).

	L-FORCE ** (Nm)								*p*-Value *			
	For Paretic Legs				For Non-Paretic Legs							
	At T0		At T1		At T0		At T1		*P*1 [1]	*P*2 [2]	*P*3 [3]	*P*4 [4]
	Mean	SD	Mean	SD	Mean	SD	Mean	SD				
Hip Ext. [5]	17.2	±15.85	24.5	±21.44	38	±23.94	50	±35.50	<0.05	<0.05	ns	ns
Hip Flex. [6]	28.6	±18.46	38.4	±21.22	50.9	±26.24	49.8	±19.45	<0.01	ns	<0.05	ns
Knee Ext.	13.1	±9.73	17.4	±12.76	37.4	±16.87	29.5	±16.77	<0.01	<0.05	ns	ns
Knee Flex.	12.6	±13.32	14.6	±12.43	36.9	±14.48	37.7	±17.42	<0.01	<0.01	ns	ns

* *p*-value obtained using Wilcoxon signed-rank test; statistically significant at $p < 0.05$; ns = non-significant. ** L-FORCE = Lower limb-force. [1] *P*1 = *p*-value comparing L-FORCE at basal assessments (T0) between paretic legs and non-paretic legs. [2] *P*2 = *p*-value comparing L-FORCE at one-month follow-up (T1) between paretic legs and non-paretic legs. [3] *P*3 = *p*-value comparing L-FORCE of paretic legs at T0 and T1. [4] *P*4 = *p*-value comparing L-FORCE of non-paretic legs at T0 and T1. [5] Ext. = Extension. [6] Flex. = Flexion.

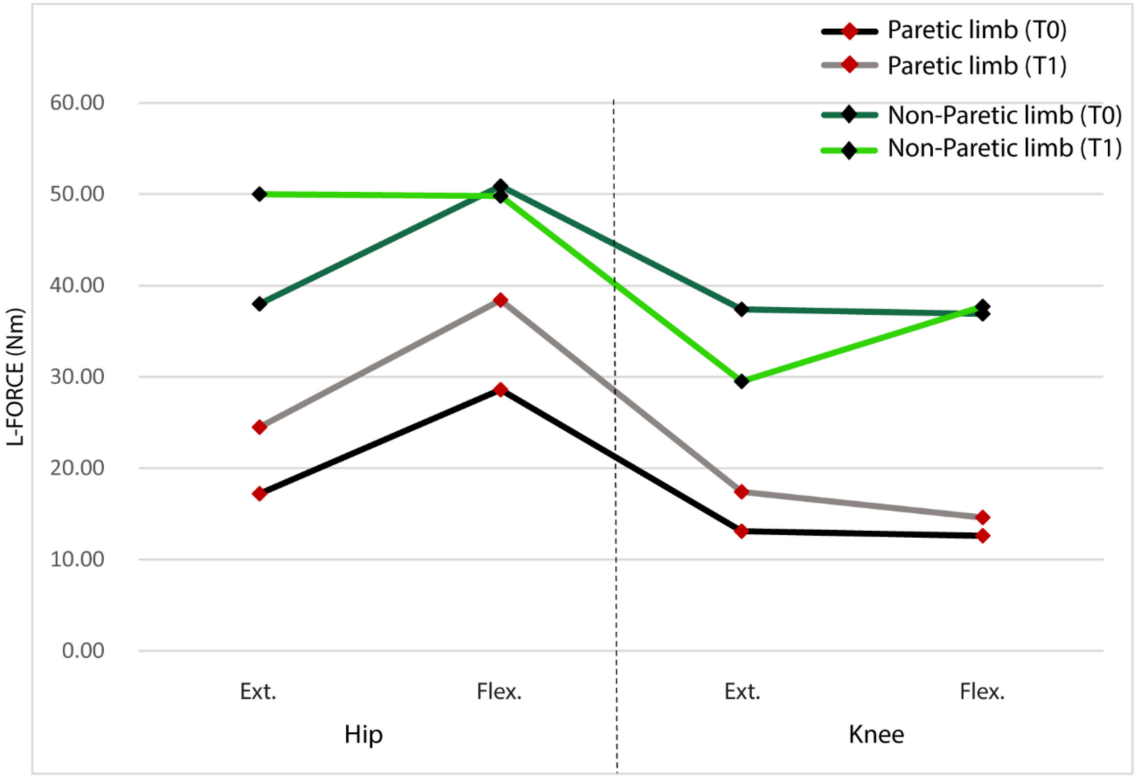

Figure 2. L-FORCE (lower limb-force) measures (mean) of paretic and non-paretic limb at basal assessments T0 and one-month follow-up T1.

3.3. Range of Motion

Table 4 shows the mean of the L-ROM measures (range of motion assessment) for the paretic and non-paretic lower limb at basal assessments (T0) and at one-month follow-up (T1) for hip and knee. In addition, Table 4 presents the significance values (*p*-value) estimated using the Wilcoxon signed-rank test by comparing the L-ROM values obtained for the paretic and the non-paretic legs, at T0 and T1, as detailed in the footers of the same table (Table 4). Figure 3 shows a plot of the mean measures of the range of motion obtained for paretic and non-paretic limb at T0 and at T1.

Table 4. Mean and standard deviation (SD) of the L-ROM (range of motion) measures (°) for paretic and non-paretic limbs at basal assessments (T0) and one-month follow-up (T1).

	L-ROM ** (°)								*p*-Value *			
	For Paretic Legs				For Non-Paretic Legs				*P*1 [1]	*P*2 [2]	*P*3 [3]	*P*4 [4]
	At T0		At T1		At T0		At T1					
Hip	20.00	±13.90	26.10	±15.66	37.00	±10.19	40.90	±11.73	<0.05	<0.01	<0.05	ns
Knee	19.00	±20.73	21.60	±19.94	58.20	±16.25	60.30	±18.43	<0.01	<0.01	ns	ns

* *p*-value obtained using Wilcoxon signed-rank test; statistically significant at $p < 0.05$; ns = non-significant. ** L-ROM = Lower limb-range of motion. [1] *P*1 = *p*-value comparing L-ROM at basal assessments (T0) between paretic legs and non-paretic legs. [2] *P*2 = *p*-value comparing L-ROM at one-month follow-up (T1) between paretic legs and non-paretic legs. [3] *P*3 = *p*-value comparing L-ROM of paretic legs at T0 and T1. [4] *P*4 = *p*-value comparing L-ROM of non-paretic legs at T0 and T1.

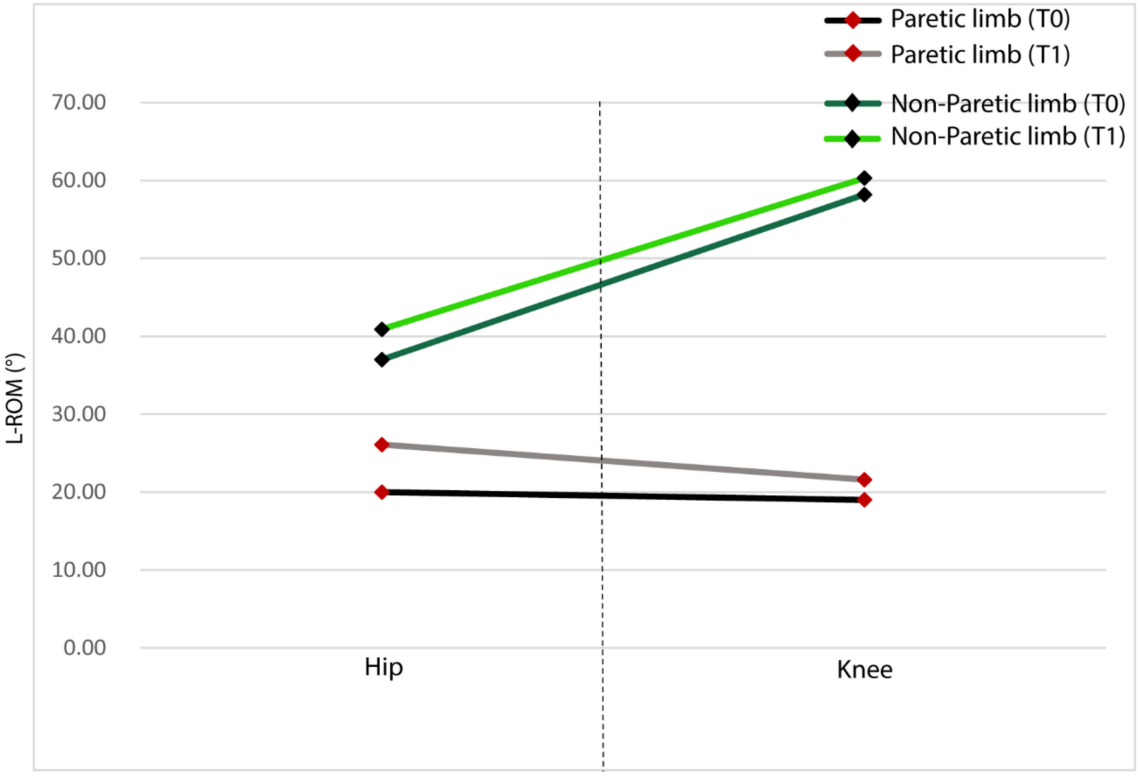

Figure 3. L-ROM (lower limb-range of motion) measures (mean) of paretic and non-paretic limb at basal assessments T0 and one-month follow-up T1.

According to results in Table 4 and Figure 3, the range of motion (ROM) values of the paretic legs were lower than those of non-paretic legs during the basal assessments (T0) and these ROM differences were statistically significant ($p < 0.05$). Also, at one-month follow-up (T1) the ROM values of the paretic legs continued to be lower than those of non-paretic legs and these ROM differences were statistically significant ($p < 0.05$). The ROM values of the paretic legs at one-month follow-up (T1) were greater than those at basal assessment (T0) but these value differences were statistically significant ($p < 0.05$) only for the hip. The ROM values of the non-paretic legs at one-month follow-up (T1) were greater than those at basal assessment (T0) but these ROM differences were not statistically significant.

4. Discussion

Using the L-STIFF tool, the measured values of the paretic legs were greater than those of the non-paretic legs during the basal assessments (T0) and these value differences were statistically

significant except for knee flexion at an angular velocity of 30°/s. Analogous results were observed at one-month follow-up (T1) except for hip extension at 22.50°/s and at 90°/s. This means an increased resistance to the passive joint movement of paretic legs in comparison with non-paretic legs, that is, greater stiffness [8]. Since stiffness is related to the patient's spasticity, these data allow to deduce that spasticity was already present during the early post-stroke phase and that the L-STIFF tool was able to measure these stiffness changes. Spasticity is a motor complication of strokes that usually occurs gradually from the acute phase to the chronic phase. Although some authors suggest that spasticity is rare during the first month after stroke [26–28], recent studies suggest that spasticity occurs during the early period following stroke [29] as it occurred to the subjects of this study. The detected differences in the data between the paretic and non-paretic legs were statically significant even though a cohort of only 10 subjects was used. As in other studies, this tool delivered consistent results [11,13]. Using L-FORCE and L-ROM tools, the measured values for both joint torque and range of motion (ROM) of the paretic legs were lower than those of the non-paretic legs at T0 and these value differences were statistically significant. Analogous results were observed at T1 except for hip flexion torque. These results are consistent since after a stroke both joint torque and ROM are affected in the paretic leg probability due to decline of the excitability of descending motor pathways [28,29] and the changes in the rate of coding and recruitment of paretic motor units [30]. Therefore, L-FORCE and L-ROM tools were able to measure the joint toque and ROM changes between paretic and non-paretic legs during the subacute phase of stroke.

Comparing basal assessments (T0) with one-month follow-up (T1) for each limb (paretic and non-paretic), using the L-STIFF tool, the measured values of the stiffness of the paretic legs at T1 were lower than those at T0 but this decrease was not statistically significant. Using L-FORCE and L-ROM tools, the joint torque and the ROM for the paretic legs at T1 was greater than that at T0 but the differences were not statistically significant except for hip flexion torque ($p < 0.05$) and hip ROM ($p < 0.05$). This means that paretic legs improved their stiffness, joint torque and ROM after one month of intensive rehabilitation treatment including Lokomat, as expected, and the L-STIFF, L-FORCE and L-ROM tools were able to measure the small changes but the low number of patients influenced the statistical significance. However, it is important to mention that a poor statistical significance does not mean that the results do not have practical importance. As well as several studies on care and rehabilitation focused on patients with strokes, the aim of the treatments is early intervention and intensive training [31] since studies of animal models demonstrated a time-limited period of heightened plasticity after focal brain injuries [32,33]. Regarding the non-paretic legs, one month later the stiffness and the joint torque fluctuated without a consistent trend and without statistical significance. On the other hand, the ROM was improved without statistical significance. These results were expected since the training of the non-paretic legs is limited by the performance of the paretic legs. Therefore, the non-paretic legs do not train to the best of their ability and thus they do not present significant changes.

The main limitation of this study was the low number of patients. Accordingly, the absence of statistical significance in the improvement of joint torque, increase in joint excursion, and reduction of stiffness was probably influenced by this. Unfortunately, during the early stages of the disease, the evaluation of joint torque and joint excursion cannot include patients who were hemiplegic, or who were not able to understand indications. Indeed, to evaluate joint torque and joint excursion, the active and voluntary participation of the patient is required, as well as the skills to adequately understand the task. Another limitation of this study is the high cost of Lokomat that may reduce its widespread use and, therefore, the utilization of the data it can provide. An additional limitation is that no measurements were carried out with another instrument to compare the Lokomat results.

5. Conclusions

Paretic legs compared with contralateral legs presented a lower joint torque and range of motion (ROM), and a greater stiffness at both basal assessments (T0) and one-month follow-up

(T1). Furthermore, the joint torque and ROM differences between paretic and non-paretic legs were statistically significant even though a cohort of only 10 subjects was used. The L-STIFF, L-FORCE and L-ROM tools were able to measure the stiffness, joint torque and ROM changes between paretic and non-paretic legs at both T0 and T1 during the early post-stroke phase. One month after robotic gait training with Lokomat Pro V6, despite the absence of changes with statistical significance, a trend towards joint torque and ROM improvement and stiffness reduction was documented for the paretic legs. The L-STIFF, L-FORCE and L-ROM tools were able to measure the small changes of stiffness, joint torque and ROM one month later after the rehabilitation training for the paretic legs but the low number of patients influenced the statistical significance of the changes. Since weakness and spasticity are directly related to joint torque and stiffness, Lokomat tools allow to get an estimation of weakness and spasticity through a precise quantification of motor impairment in subacute hemiparetic patients with their first ever stroke. Further studies with a larger population size and a longer observation period are required to verify the feasibility of Lokomat tools in monitoring the evolution of joint torque, ROM, and stiffness during the recovery of patients after a stroke.

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