Research paper

Title: Intra and inter-tester reliability of spasticity assessment in standing position in children and adolescents with cerebral palsy using a paediatric exoskeleton

Authors: Yosra Cherni[1,2*], Laurent Ballaz[2,3], Geneviève Girardin-Vignola[2], Mickael Begon[1,2]

Affiliations:
(1) École de kinésiologie et des sciences de l'activité physique, Faculté de Médecine, Université de Montréal, Montréal, Québec, Canada
(2) Centre de réadaptation Marie-Enfant, CHU Sainte-Justine, Montréal, Québec, Canada
(3) Département des sciences de l'activité physique, Université de Québec à Montréal, Montréal, Québec, Canada

Corresponding author: Yosra Cherni[1,2]
Address: Centre de recherche du Centre de réadaptation Marie-Enfant, CHU Sainte-Justine, 5200 rue Bélanger, H1T 1C9 Montréal, Québec, Canada
Tel : (001) 438-806-6462
Email: yosra.cherni@umontreal.ca

Declaration of interest: The authors declare that they have no competing interest.

ORCID : Yosra Cherni https://orcid.org/0000-0001-9574-3453

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Running title: Reliability of the Lokomat spasticity assessment.

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Abstract (244)

Background: The L-STIFF tool of the Lokomat evaluate the hip and knee flexors and extensors spasticity in a standing position. It moves the lower limb at a controlled velocity, measuring joint resistance to passive movements. Since its reliability in children with cerebral palsy remains unknown, our goal was to evaluate the relative and absolute reliability of L-STIFF in children with cerebral palsy.

Methods: Reliability was determined in 16 children with cerebral palsy by two experienced therapists. The changes in resistive torque in hip and knee in both flexion and extension were measured. Relative and absolute reliability were estimated using the intra-class correlation coefficient, standard error of measurement and minimal detectable change. Reliability was assessed on three levels: (1) intra- and (2) inter-tester within session, and (3) intra-tester between sessions.

Results: Intra-class correlation coefficients were moderate to excellent for intra-tester reliability (all $p \leq 0.01$). The standard error of measurement ranged from 0.005 to 0.021 Nm/° (i.e., 7 to 16%) and minimal detectable change from 0.014 to 0.059 Nm/°. Inter-tester Intra-class correlation coefficients ranged from 0.32 to 0.70 (all $p \leq 0.01$), standard error of measurement from 0.012 to 0.029 Nm/° (i.e., 6 to 39 %) and minimal detectable change from 0.033 to 0.082 Nm/°. L-STIFF reliability was better during fast and medium movement speeds compared to slow speeds.

Conclusions: The assessment tool L-STIFF is a promising tool for quantifying lower limb spasticity in children with cerebral palsy in a standing position. However, the results should be interpreted carefully.

Keywords: Psychometric properties, Muscle tone, Mobility, Cerebral palsy, Lokomat

1. Introduction

Spasticity is the most common motor disorder in children with cerebral palsy (CP) with a prevalence of 80% to 90%. Spasticity is an involuntary muscle contraction following sensory input induced by muscle stretch and it has been characterized as a velocity-dependent phenomenon [1]. Spasticity results in a greater than normal resistance to externally imposed movements, and this resistance increases with velocity [1,2]. Although spasticity is of neural origin [1], there is recent evidence that spasticity involves a structural and functional changes in skeletal muscle [3–5]. It hampers normal muscle lengthening during growth and is thus can contribute to the development of secondary muscle and soft tissue contractures and to skeletal deformation [5–7]. These muscle contractures and skeletal deformities may result in lever arms modifications, which alter joint moments during walking [8].

Characterization and quantification of muscle spasticity are important to plan medical or surgery interventions (e.g., repetitive passive mobilization, injection of botulinum toxin or selective dorsal rizhotomy). To do so, reliable clinical tests are required for daily clinical monitoring of muscle spasticity [10,11]. Modified Ashworth Scale (MAS) and Modified Tardieu Scale (MTS) are frequently used in clinical practice to assess muscle response to a quick passive stretch applied by the therapist. The MAS is a 6-point ordinal scale qualifying the resistance of muscles to passive movement [12]. Using a single speed measure, the MAS tends to cluster muscles into broad severity categories, thereby limiting its ability to detect response to treatment [13]. The MTS was developed to qualify the resistance to passive stretching at three velocities also on a 6-point ordinal rating scale. The therapist measures two resulting joint angles using a goniometer: the angle of catch at which a muscle response (stretch reflex) is provoked by the fast velocity stretch (R1) and the angle of full passive range of motion obtained with low speed stretching (R2). The difference between these two values (R2-R1) is thought to describe the level of dynamic contracture at the joint [14,15]. However, this assessment is affected by the difficulty of controlling the speed movement during the testing as well as the experience of the examiner [16]. Moreover, several studies pointed out the low inter-tester reliability of the MAS and MTS in children with CP [17]. The above-cited limitations of these clinical tests result in a misestimation of spasticity. Finally, due to the discrepancies between spasticity manifestation in sitting or lying position and how spasticity may contribute to walking limitations, the transfer of clinical assessment to functional limitations remains uncertain [16]. Complementary methods are needed to improve the reliability of spasticity measurements and to assess spasticity in a standardized and functional position.

The Lokomat, the most used robotic gait trainer, provides isometric strength (L-Force) and spasticity (L-STIFF) assessment tools [18,19]. L-STIFF tool measures the changes in resistive torque in hip and knee in both flexion and extension during predefined passive movements by moving the joint at a constant velocity. With L-STIFF tools, both the range of motion and the velocity of the movement are controlled. L-STIFF offers continuous data and thus a wider range of possible outcomes which is more adequate for longitudinal follow-ups [20]. Moreover, apart from the patient setup which depends on the examiner, L-STIFF testing execution is not affected by variations usually observed among examiners [18]. For its clinical validation, L-STIFF measurement at different velocity tool was first compared to MAS on patients with central nervous lesions [18,21]. The MAS score correlated with L-STIFF measurement at the highest velocity, only [18,21]. A high stiffness value is assumed to correspond to strong spasticity [21,22]. Afterwards, Schmartz et al., [23] evaluated the intra-tester reliability of L-STIFF in children with CP (n=9) and highlighted excellent reliability (intraclass correlation coefficients (ICCs) = 0.83–0.97). However, studies with larger sample size and additional psychometric properties (i.e., inter-session and inter-tester reliability) are required for the clinical use of L-STIFF. In particular, inter-tester and inter-session reliability are needed for daily clinical follow-up of spasticity. The aim of the present study was to assess intra-and inter-tester reliability of L-STIFF.

2. Material and methods

2.1. Participants

The sample size estimation was based on a significance level of 0.05, a power of 0.80, and an ICC-value between 0.60 (fair) and 0.90 (excellent) for both intra and inter-tester reliability analysis. The minimal sample size was 15 for this reliability analysis. In the present study, 16 children and adolescents with CP (mean ± standard deviation, age: 10±3 years (range: 7–19 years), mass: 30±9 kg, height: 131±9 cm, 7 Females and 9 Males) were included. Participants had a Gross Motor Function Classification System (GMFCS) level II (n = 10) and III (n = 6). The inclusion criteria were: (1) children and adolescents with a diagnostic of spastic CP, (2) ability to communicate fear, discomfort or pain, as evaluated by the physiotherapist, (3) understanding simple instructions and, (4) a femur length of 23-35 cm (to fit in Lokomat pediatric orthosis). Children were excluded if they had received: (1) spasticity medication before the assessment, (2) botulinum toxin injections six months prior to the assessment and, (3) an intrathecal baclofen pump or a surgical intervention during the last 12 months. This study was approved by the Research Ethics Board of UHC Sainte-Justine.

2.2. Reliability assessments

Hip and knee spasticity were assessed by L-STIFF tool using the pediatric version of Lokomat Pro (Hocoma AG, Volketswil, Switzerland). Technical utilization of L-STIFF tool has been previously described [18,21]. Briefly, the participant is lifted above the treadmill (unloading from 100% of his body weight) to be able to freely move hip and knee joints without touching the ground with the feet (see Figure 1).

**** Insert **Figure 1******

Then, the Lokomat performed a controlled displacement of each of the four actuated joints (i.e., left and right hip and knee) in flexion and extension at three velocities (22.5°/s, 45°/s and 90°/s for the hip and 30°/s, 60°/s and 120°/s for the knee). The range of motion was set according to patient capacity and can be reduced for patients with contractures or range of motion limitations. Maximal range of motion is fixed at 46° in the hip and at 55° in the knee joint. The protocol was divided into two measurement sessions to assess inter and intra-tester reliability (see Figure 2).

**** Insert **Figure 2******

Stage 1: Inter-tester & Intra-tester within same session reliability

Each participant was tested independently by two experienced Lokomat users (GG and YC) on the same day. To ensure proper reliability assessment, the order of the two testers was randomized and each tester was blinded to the results obtained by the other. Each participant accomplished a familiarization trial of L-STIFF test followed by two real tests. Participants were asked to relax completely and to avoid any voluntary muscle contraction during the test. During each test, the instruction "3-2-1-Go" was given verbally by the tester. A 2-min rest was given between the two blocks of tests. During the assessments, we did not make noise or talk to keep the patient as relaxed as possible during the test. Then, the participant was taken out of the Lokomat and had a short (15 min) break period. Thereafter, the second tester reinstalled the participant into the

Lokomat and repeated the same procedure. Measures acquired during this stage were also used to assess *intra-tester* within same session reliability for each tester since each tester measured the torque twice.

Stage 2: Intra-tester (between days) reliability

In the second part of the protocol, *intra-tester reliability* (between days) was conducted by the tester GG a week later (see Figure 1). Participant was installed into the Lokomat by tester GG who used the same anthropometric settings as in stage 1. Then, participant performed two L-STIFF trials. Overall, L-STIFF tool took about 2.5 min to measure hip and knee flexion and extension torques.

2.3. Statistical analysis

An analysis of variance (ANOVA)-based ICC was used to evaluate the relative reliability of L-STIFF measurements at each measurement speed. To test reliability, ICCs with 95% confidence intervals (two-way random-effect models) were used. ICC scores were compared with the following scale for interpretation of correlation: excellent (1.00 – 0.81), good (0.80 – 0.60), moderate (0.41 – 0.60), fair (0.21 – 0.40) and poor (< 0.20) [24]. Standard error of measurement (SEM) and the 95% CI of the minimal detectable change (MDC) were calculated to evaluate L-Stiff absolute reliability [25]. The ICC reflects the degree of consistency of a measurement. The SEM and MDC provide information about the expected trial-to-trial measurement error [26]. As it is recognized that there is a large inter-limb strength difference in children with CP, statistical analysis considered each side independently for all the tests (n=2x16), as done in previous studies [27,28]. The level of significance was set to p-value < 0.05. All statistical analysis was performed with SPSS (version 25.0, IBM SPSS Incorporated, Chicago, IL, USA).

3. Results

Intra-tester reliability

The median, minimum and maximum values and first and third quartiles of measured hip and knee torques are reported in **Figure 3**. For *intra-tester* (same session), ICCs varied from 0.69 to 0.95, SEM from 0.002 to 0.007, and MDC from 0.009 to 0.021 Nm/° (see Table 1). For *intra-tester* reliability (between days), ICCs ranged from 0.49 to 0.89 (all $p \leq 0.01$), while SEM varied from 0.005 to 0.021 Nm/° (*i.e.*, 7 to 16%) and MDC from 0.014 to 0.059 Nm/°. The highest SEM (0.005 to 0.021 Nm/°) and MDC (0.025 to 0.059 Nm/°) values were observed at fast velocity (see Table 2).

**** Insert **Figure 3******

Table 1: Intra-tester (same-session) reliability of L-STIFF measurements in hip and knee flexion and extension (all p≤0.01)

	ICC			SEM (Nm/°)			MDC (Nm/°)		
	Slow	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**
Hip flexion	0.86	0.95	0.92	0.006 (4%)	0.003 (2%)	0.003 (2%)	0.017	0.008	0.009
Hip extension	0.92	0.93	0.95	0.004 (2%)	0.003 (2%)	0.002 (1%)	0.010	0.009	0.006
Knee flexion	0.77	0.82	0.83	0.006 (15%)	0.004 (9%)	0.004 (6%)	0.016	0.0100	0.012
Knee extension	0.87	0.89	0.69	0.004 (8%)	0.003 (6%)	0.007 (9%)	0.011	0.008	0.021

Abbreviation: ICC: Intraclass correlation coefficient; SEM: standard error of measurement in units of measure and in percentage (%); MDC: minimal detectable change.

Table 2: Intra-tester (between days) reliability of L-STIFF measurements in hip and knee flexion and extension (all p≤0.01)

	ICC			SEM (Nm/°)			MDC (Nm/°)		
	Slow	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**
Hip flexion	0.65	0.63	0.58	0.015 (8%)	0.018 (9%)	0.021(10%)	0.042	0.049	0.059
Hip extension	0.49	0.66	0.62	0.021 (11%)	0.015 (8%)	0.017 (8%)	0.059	0.042	0.047
Knee flexion	0.89	0.84	0.84	0.005 (7%)	0.008 (11%)	0.010 (10%)	0.014	0.024	0.029
Knee extension	0.70	0.89	0.88	0.015 (16%)	0.007 (7%)	0.009 (8%)	0.041	0.018	0.025

Abbreviation: ICC: Intraclass correlation coefficient; SEM: standard error of measurement in units of measure and in percentage (%); MDC: minimal detectable change.

Inter-tester reliability

Inter-tester ICCs ranged from 0.32 to 0.70 (all $p \leq 0.01$) and SEM from 0.012 to 0.029 Nm/° (*i.e.*, 6 to 39%). For the hip flexors and extensors, fair to moderate inter-tester reliability (ICCs =0.32 – 0.46) was found for movement with slow velocity, whereas moderate to good reliability was found with peak torque measurements at fast velocity (ICCs=0.68 – 0.70). Concerning the knee flexors and extensors, ICCs were moderate for all speeds ranging from 0.43 to 0.55. The highest SEM values were observed at slow velocities for knee flexion and extension (34 and 39%, respectively). Minimal detectable changes ranged from 0.033 to 0.082 Nm/° with highest values again observed at slow velocity (see Table 3).

Table 3: Inter-tester reliability of L-STIFF measurements in hip and knee flexion and extension (all $p<0.05$)

	ICC			SEM (Nm/°)			MDC (Nm/°)		
	Slow	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**
Hip flexion	0.46	0.49	0.68	0.028 (16%)	0.028 (16%)	0.016 (8%)	0.079	0.078	0.043
Hip extension	0.32	0.60	0.70	0.027 (15%)	0.017 (9%)	0.012 (6%)	0.074	0.047	0.033
Knee flexion	0.55	0.50	0.47	0.020 (34%)	0.020 (33%)	0.023 (26%)	0.057	0.054	0.063
Knee extension	0.48	0.54	0.43	0.029 (39%)	0.020 (27%)	0.026 (27%)	0.082	0.054	0.072

Abbreviation: ICC: Intraclass correlation coefficient; SEM: standard error of measurement in units of measure and in percentage (%); MDC: minimal detectable change.

4. Discussion

The present study aimed to evaluate the reliability of L-STIFF tool to assess hip and knee spasticity in a standing position in a group of children and adolescents with spastic CP (GMFCS level II and III). Our main findings were that: **(1)** the most reliable measurement using L-STIFF tool was intra-tester within the same session, followed by intra-tester between sessions, and then inter-tester, and **(2)** L-STIFF reliability was higher during fast and medium movement speeds compared to slow speeds.

L-STIFF relative reliability

In a feasibility study (n=9), Schmartz et al., [23] reported good intra-tester reliability of L-STIFF (ICCs=0.83 – 0.97) in children with CP assessed by one tester in only one session. Our intra-tester ICC values (n=16; same session; ICCs=0.69 – 0.95) were in good agreement with those of Schmartz et al., [23] except for the knee extension at fast speed for which our ICC was slightly lower (ICC=0.69). This reliability differences could be due to the between-participants variability within the study samples (GMFCS II to V in [23] *vs.* GMFCS II and III in our study), as ICC score is strongly dependent on the between participant variability [29]. More importantly, L-STIFF intra-tester reliability (between days) was overall better (ICCs=0.49 – 0.89) than those found with the MAS (ICCs=0.21 – 0.82) and MTS (ICCs=0.38 – 0.93) in a sample of 18 children with CP (GMFCS level I to V) [30]. When measured at different days by the same tester and with the same settings, intra-tester ICCs were good to excellent for the knee flexors and extensors measurements (ICCs=0.70 – 0.89) and moderate to good for hip flexors and extensors (ICCs=0.49 – 0.66). Considering the results of Yam et al., [31], again, inter-tester reliability of L-STIFF (ICCs=0.32 – 0.70) was better than MAS

(ICCs=0.27 – 0.56) but slightly lower than the MTS (ICCs=0.55 – 0.74). Compared to a sample of 17 children with CP (GMFCS levels II and III) more similar to ours [31], L-STIFF inter-tester reliability was slightly better than the reliability found with the MTS (ICCs=0.22 – 0.71). Overall, L-STIFF relative reliability is better than MAS and MTS.

Sources of variability and errors

While the L-STIFF execution relies on the machine only, the patient setup into the Lokomat depends on the assessor. For that reason, the L-STIFF intra-tester (within and between sessions) reliability was generally higher than the inter-tester values. As for the isokinetic dynamometer [32], a source of error in L-STIFF measurements could mainly come from the misalignment of axes between participant joints and the Lokomat motors. This point is generally underlined and is the object of recommendations in several studies regarding the use of the isokinetic dynamometer [32,33]. Although the Lokomat is multi-articular, this recommendation is even more applicable for L-STIFF tool. A special care must be given to the installation and alignment of the child into the Lokomat to minimize erroneous spasticity measurement. Above all, standardization and training should be further improved to reduce extrinsic error when different testers perform the measurement. In addition to error due to patient setup, the variability of L-STIFF measurements can be due to intrinsic factors (*e.g.*, abnormal muscle tone change, muscle voluntary contraction). It could also come from the repetitive movement. In particular, multiple studies have highlighted a decrease in resistive torque in patients with spasticity after repeated passive movements by using an isokinetic dynamometer [34,35]. By performing eight passive movements four times at three different speeds over a span of 1 hour, muscle stretching or reflex habituation may have occurred. Thence, the absolute reliability should also be investigated and considered in the interpretation of results of L-STIFF.

L-STIFF absolute reliability

Although *relative* reliability addresses the degree to which subjects keep their rank in a sample through repeated measures, *absolute* reliability (*i.e.*, SEM and MDC) informs about the measurement errors in absolute values and the limit for the smallest change that indicates a real clinical improvement following an intervention. Overall, 84% of our SEM values were smaller than 20% of the grand mean of measurements (all intra-tester SEM values are <20%). From a clinical point of view [36], our SEM values seem reasonable and confirm that L-STIFF measurements can be used to detect real changes for a group of children with CP. Our absolute SEM values were overall smaller than Schmartz et al.' results [23], which is probably due to the severity of impairment that was more important in their group of children (including children with GMFCS IV and V). In regards to the effect of anti-spastic treatment reported in literature, L-STIFF measurements can be deemed sensitive enough to differentiate between pre and post treatment interventions [13,23].

Clinical implications

Spasticity clinical scales provided a non-specific and non-controlled testing velocity, which is problematic to evaluate a velocity-dependent mechanism. [21,31]. The advantage of L-STIFF is to assess spasticity at three controlled movement velocities in a standing position. When walking, children with CP move their lower limb joints at various speeds [38,39]. The slow (22.5°/s), medium (45°/s) and fast (90°/s) velocities used in L-STIFF measurement at the hip correspond to values measured at this joint during terminal swing and the pre-swing phase of gait. Such matching velocities may better inform on spasticity implications during gait [16]. Regarding the knee measurements, L-STIFF testing velocities (30, 60 and 120°/s) were overall slower than knee angular velocities during walking [38,40]. Tuzson et al., [41] reported a peak knee angular velocities during fast walking ranged from 100° to 450°/s in patients with CP and were significantly slower than the knee angular velocities of typically developed participants. In the same study, the authors determined spastic velocity thresholds of the knee joint via an isokinetic dynamometer. Knee spastic threshold velocity was on average 175°/s ± 63.8°/s [41]. Later, Damiano et al., [40] reported a moderate correlation between the assessment of hamstring and quadriceps stiffness at 120°/s and maximum extension velocity (r = -0.47 and -0.41, respectively) and maximum flexion velocity (r = -0.50 and -0.39, respectively) during walking at comfortable speed. The results of these studies imply that 120°/s may probably be too low to elicit spastic responses, particularly in patients who only have moderate spasticity [40–42]. L-STIFF testing velocities in the knee are probably more suitable for children with more pronounced spasticity. Finally, L-STIFF allows evaluating spasticity at three different velocities and in standing position, it could be used to refine the relationship between lower limb spasticity and joint biomechanics during walking.

Study limitations

This study had some limitations that need to be considered when interpreting the results. Firstly, the results are valid for children and adolescents with CP with GMFCS levels II and III which limit the results generalizability but correspond to the children and adolescents with CP who benefit the most of gait rehabilitation with the Lokomat. Secondly, cognitive impairment was not formally assessed, while it could be a source of variability when assessing motor function in people with CP [43]. Fourthly, limited intrinsic/extrinsic errors may be introduced by repeated stretch repetitions and the learning effect of the measurement routine. Fifthly, L-STIFF quantifies only the spasticity of hip and knee flexors and extensors while spasticity can affect various lower limb muscles (e.g., hip adductors, plantar-flexors) in children and adolescents with CP.

5. Conclusion

Based on the outcomes of the present reliability study, L-STIFF measurements were more reliable when the same tester, rather than different testers performed the assessment. When different testers perform the measurement, standardization and training should be improved to minimize the extrinsic error as much as possible. Moreover, our SEM and MDC should be systematically used for longitudinal follow-up of spasticity to determine if the change exceeds uncertainties or not. On the whole, L-STIFF of the Lokomat is a promising tool for evaluating lower limb spasticity in children and adolescents with CP in a more functional posture than traditional clinical scales.

Disclosure of interest

The authors declare that they have no competing interest.

REFERENCES

[1] Lance JW. What is spasticity? Lancet Lond Engl 1990;335:606.

[2] Lance JW. The control of muscle tone, reflexes, and movement: Robert Wartenberg Lecture. Neurology 1980;30:1303–13.

[3] Lieber RL, Fridén J. Spasticity causes a fundamental rearrangement of muscle-joint interaction. Muscle Nerve 2002;25:265–70.

[4] Lieber RL, Steinman S, Barash IA, Chambers H. Structural and functional changes in spastic skeletal muscle. Muscle Nerve 2004;29:615–27. doi:10.1002/mus.20059.

[5] Bar-On L, Molenaers G, Aertbeliën E, Van Campenhout A, Feys H, Nuttin B, et al. Spasticity and Its Contribution to Hypertonia in Cerebral Palsy. BioMed Res Int 2015;2015. doi:10.1155/2015/317047.

[6] Morrell DS, Pearson JM, Sauser DD. Progressive bone and joint abnormalities of the spine and lower extremities in cerebral palsy. Radiogr Rev Publ Radiol Soc N Am Inc 2002;22:257–68. doi:10.1148/radiographics.22.2.g02mr19257.

[7] Willerslev-Olsen M, Choe Lund M, Lorentzen J, Barber L, Kofoed-Hansen M, Nielsen JB. Impaired muscle growth precedes development of increased stiffness of the triceps surae musculotendinous unit in children with cerebral palsy. Dev Med Child Neurol 2018;60:672–9. doi:10.1111/dmcn.13729.

[8] Gage JR, Schwartz MH, Koop SE, Novacheck TF. The Identification and Treatment of Gait Problems in Cerebral Palsy. John Wiley & Sons; 2009.

[9] Rose J, Haskell WL, Gamble JG, Hamilton RL, Brown DA, Rinsky L. Muscle pathology and clinical measures of disability in children with cerebral palsy. J Orthop Res 1994. doi:10.1002/jor.1100120603.

[10] Harburn KL, Hill KM, Vandervoort AA, Helewa A, Goldsmith CH, Kertesz A, et al. Spasticity measurement in stroke: a pilot study. Can J Public Health Rev Can Sante Publique 1992;83 Suppl 2:S41-45.

[11] Simons DG, Mense S. Understanding and measurement of muscle tone as related to clinical muscle pain. Pain 1998;75:1–17.

[12] Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. Phys Ther 1987;67:206–7.

[13] Bar-On L, Van Campenhout A, Desloovere K, Aertbeliën E, Huenaerts C, Vandendoorent B, et al. Is an instrumented spasticity assessment an improvement over clinical spasticity scales in assessing and predicting the response to integrated botulinum toxin type a treatment in children with cerebral palsy? Arch Phys Med Rehabil 2014;95:515–23. doi:10.1016/j.apmr.2013.08.010.

[14] Akpinar P, Atici A, Ozkan FU, Aktas I, Kulcu DG, Sarı A, et al. Reliability of the Modified Ashworth Scale and Modified Tardieu Scale in patients with spinal cord injuries. Spinal Cord 2017;55:944–9. doi:10.1038/sc.2017.48.

[15] Held J-P, Pierrot-Deseilligny E. Rééducation motrice des affections neurologiques [par] Jean-Pierre Held [et] Emmanuel Pierrot-Deseilligny. Paris: Baillière; 1969.

[16] Banky M, Ryan HK, Clark R, Olver J, Williams G. Do clinical tests of spasticity accurately reflect muscle function during walking: A systematic review. Brain Inj 2017;31:440–55. doi:10.1080/02699052.2016.1271455.

[17] Flamand VH, Massé-Alarie H, Schneider C. Psychometric evidence of spasticity measurement tools in cerebral palsy children and adolescents: a systematic review. J Rehabil Med 2013;45:14–23. doi:10.2340/16501977-1082.

[18] Riener R, Lünenburger L, Colombo G. Human-centered robotics applied to gait training and assessment. J Rehabil Res Dev 2006;43:679–94.

[19] Cherni Y, Girardin-Vignola G, Ballaz L, Begon M. Reliability of maximum isometric hip and knee torque measurements in children with cerebral palsy using a paediatric exoskeleton - Lokomat. Neurophysiol Clin Clin Neurophysiol 2018. doi:10.1016/j.neucli.2018.12.001.

[20] Riener R, Lünenburger L, Colombo G. Human-centered robotics applied to gait training and assessment. J Rehabil Res Dev 2006;43:679–94.

[21] Lünenburger L, Colombo G, Riener R, Dietz V. Clinical assessments performed during robotic rehabilitation by the gait training robot Lokomat. 2005 IEEE 9th Int. Conf. Rehabil. Robot., IEEE Service Center; 2005, p. 345–8. doi:10.1109/ICORR.2005.1501116.

[22] Riener R, Brunschweiler A, Lünenburger L, Colombo G. Robot-supported spasticity evaluation, Bournemouth, England.: 2004, p. 287-89.

[23] Schmartz AC, Meyer-Heim AD, Müller R, Bolliger M. Measurement of muscle stiffness using robotic assisted gait orthosis in children with cerebral palsy: a proof of concept. Disabil Rehabil Assist Technol 2011;6:29–37. doi:10.3109/17483107.2010.509884.

[24] Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res 2005;19:231–40. doi:10.1519/15184.1.

[25] Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med Auckl NZ 1998;26:217–38.

[26] Rankin G, Stokes M. Reliability of assessment tools in rehabilitation: an illustration of appropriate statistical analyses. Clin Rehabil 1998;12:187–99. doi:10.1191/026921598672178340.

[27] van der Krogt MM, Doorenbosch CAM, Harlaar J. The effect of walking speed on hamstrings length and lengthening velocity in children with spastic cerebral palsy. Gait Posture 2009;29:640–4. doi:10.1016/j.gaitpost.2009.01.007.

[28] Sangeux M, Wolfe R, Graham HK. One side or two? Dev Med Child Neurol 2013;55:786–7. doi:10.1111/dmcn.12230.

[29] Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. J Chiropr Med 2016;15:155–63. doi:10.1016/j.jcm.2016.02.012.

[30] Fosang AL, Galea MP, McCoy AT, Reddihough DS, Story I. Measures of muscle and joint performance in the lower limb of children with cerebral palsy. Dev Med Child Neurol 2003;45:664–70.

[31] Yam WKL, Leung MSM. Interrater reliability of Modified Ashworth Scale and Modified Tardieu Scale in children with spastic cerebral palsy. J Child Neurol 2006;21:1031–5. doi:10.1177/7010.2006.00222.

[32] Pierce SR, Lauer RT, Shewokis PA, Rubertone JA, Orlin MN. Test-retest reliability of isokinetic dynamometry for the assessment of spasticity of the knee flexors and knee extensors in children with cerebral palsy. Arch Phys Med Rehabil 2006;87:697–702. doi:10.1016/j.apmr.2006.01.020.

[33] Deslandes S, Mariot J-P, Serveto S. Offset of rotation centers creates a bias in isokinetics: A virtual model including stiffness or friction. J Biomech 2008;41:2112–20. doi:10.1016/j.jbiomech.2008.04.038.
[34] Nuyens GE, De Weerdt WJ, Spaepen AJ, Kiekens C, Feys HM. Reduction of spastic hypertonia during repeated passive knee movements in stroke patients. Arch Phys Med Rehabil 2002;83:930–5.
[35] Nuyens G, De Weerdt W, Ketelaer P, Spaepen A, Staes F. Torque variations during repeated passive isokinetic knee movements in persons with multiple sclerosis. J Rehabil Med 2001;33:85–9.
[36] Flansbjer U-B, Holmbäck AM, Downham D, Lexell J. What change in isokinetic knee muscle strength can be detected in men and women with hemiparesis after stroke? Clin Rehabil 2005;19:514–22. doi:10.1191/0269215505cr854oa.
[37] Fonseca LA, Grecco LAC, Politti F, Frigo C, Pavan E, Corrêa JCF, et al. Use a Portable Device for Measuring Spasticity in Individuals with Cerebral Palsy. J Phys Ther Sci 2013;25:271–5. doi:10.1589/jpts.25.271.
[38] Mentiplay BF, Banky M, Clark RA, Kahn MB, Williams G. Lower limb angular velocity during walking at various speeds. Gait Posture 2018;65:190–6. doi:10.1016/j.gaitpost.2018.06.162.
[39] Cherni Y, Laforte AP, Parent A, Marois P, Begon M, Ballaz L. Lower limb extension is improved in fast walking condition in children who walk in crouch gait. Disabil Rehabil 2018;0:1–6. doi:10.1080/09638288.2018.1493158.
[40] Damiano DL, Laws E, Carmines DV, Abel MF. Relationship of spasticity to knee angular velocity and motion during gait in cerebral palsy. Gait Posture 2006;23:1–8. doi:10.1016/j.gaitpost.2004.10.007.
[41] Tuzson AE, Granata KP, Abel MF. Spastic Velocity Threshold Constrains Functional Performance in Cerebral Palsy. Arch Phys Med Rehabil 2003;84:1363–8.
[42] Jobin A, Levin MF. Regulation of stretch reflex threshold in elbow flexors in children with cerebral palsy: a new measure of spasticity. Dev Med Child Neurol 2000;42:531–40.
[43] Song C-S. Relationships between Physical and Cognitive Functioning and Activities of Daily Living in Children with Cerebral Palsy. J Phys Ther Sci 2013;25:619–22. doi:10.1589/jpts.25.619.

Figure captions :

Figure 1: Measuring position used for the spasticity assessment using L-STIFF tool.

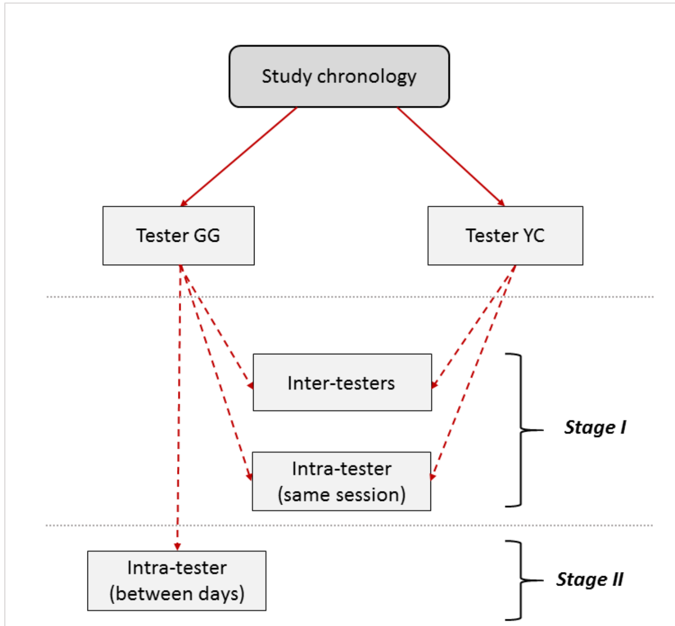

Figure 2: Schematic illustrating the three aspects of reliability (Inter-tester, intra-tester same session and intra-tester between days) evaluated during the present study.

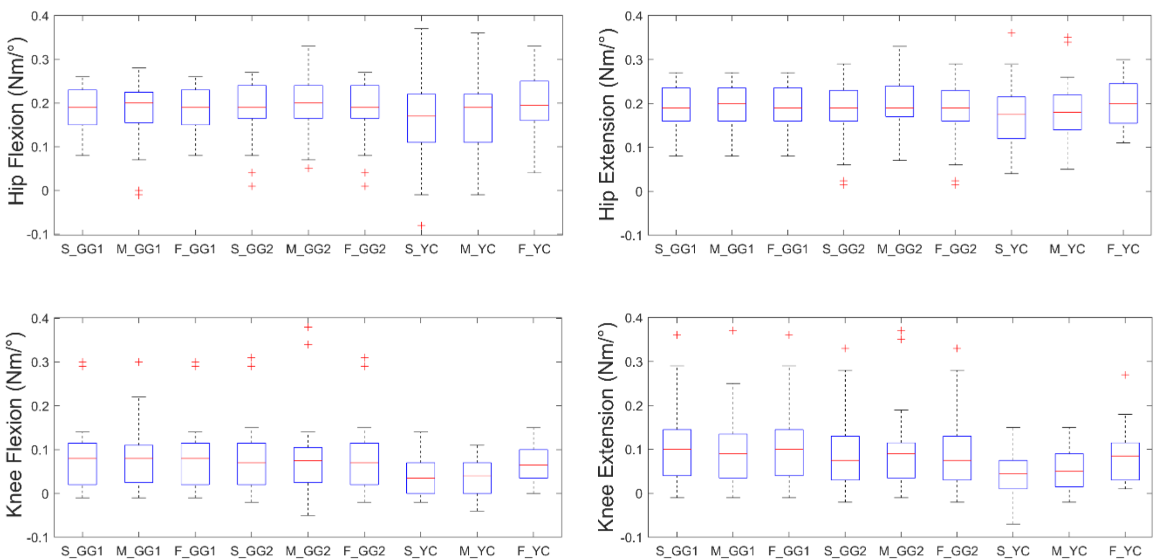

Figure 3: L-STIFF measurements box plots with median, minimum and maximum values and 25 and 75 percentiles from tester GG at day1 (GG1), tester GG at day2 (GG2) and tester YC. [Slow (S), Medium (M) and Fast (F)]. The plus signs (in red) represent the extreme values (the outliers).