ORIGINAL ARTICLE

Title: Reliability of maximum isometric hip and knee torque measurements in children with cerebral palsy using a paediatric exoskeleton - Lokomat

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

Affiliations:

(1) École de kinésiologie, Faculté de Médecine, Université de Montréal, 2100, boul. Édouard-Montpetit, H3T 1J4 Montréal, Québec, Canada

(2) Centre de réadaptation Marie-Enfant, CHU Sainte-Justine, 5200 rue Bélanger, H1T 1C9 Montréal, Québec, Canada

(3) Département des sciences de l'activité physique, Université de Québec à Montréal, C.P. 8888, succursale Centre-Ville, H3C 3P8 Montréal, Québec, Canada

Corresponding author: Yosra Cherni

Address: Centre de recherche du Centre de réadaptation Marie-Enfant, CHU Sainte-Justine, 5200 rue Bélanger, H1T 1C9 Montréal, Québec, Canada

Email: yosra.cherni@umontreal.ca

Neurophysiologie Clinique/Clinical Neurophysiology:

https://doi.org/10.1016/j.neucli.2018.12.001

Running title: Reliability of the Lokomat isometric force assessment.

Abstract

Background: The Lokomat (by L-Force tool) allows the measurement of the maximum voluntary isometric torque (MVIT) at the knee and hip joints in a standing position, as close as possible to the posture adopted during walking. However, the reliability of this measurement in children with cerebral palsy (CP) remains unknown. The main goal of this study was to evaluate inter and intra-tester reliability of a novel tool (L-Force) in CP population.

Procedure: L-Force reliability was determined in 17 children with CP by two experienced therapists. We collected cs in hip and knee flexors and extensors. Relative and absolute reliability of maximum joint torques were estimated using the intra-class correlation coefficient (ICC) and standard error of measurement (SEM), respectively. The correlation between L-Force and hand-held dynamometer (HHD) was also reported.

Findings: ICCs were good to excellent for intra and inter-tester reliability (all $p \leq 0.001$). The SEM ranged from 2.0 to 4.1 Nm (12.1 to 21.7%) within-tester and from 2.1 to 3.5 Nm (11.9 to 22.5%) between testers. The correlation was fair to good between L-Force and HHD measures ($r=[0.50\ 0.75]$; all $p<0.01$) with higher values for flexors than extensors.

Conclusion: The L-Force is a reliable tool for quantifying the hip and knee flexors and extensors torques in children with cerebral palsy with an important timesaving and in a more functional posture than traditional HHD.

Keywords: Psychometric properties, Lower limb, Muscle strength, Standing position.

Introduction

In their daily practice, physiotherapists evaluate muscle strength to identify the deficits for planning interventions and then to measure intervention effect or effectiveness [8]. In children and adolescents with cerebral palsy (CP), the evaluation of muscle strength represents a challenge, given the complex musculoskeletal condition and the poor selective motor control [14,16,48]. The outcomes of many interventions in CP, including physical training, medications and surgery affect, or are conditioned by, muscle strength. For example, in gait rehabilitation, the lower-limb muscle isometric strength is commonly assessed [31,47] as it is directly related to several functional tasks, including walking [30,34]. Unfortunately, the commonly used evaluation tools present some limitations. The Medical Research Council scale [26], based on nonlinear categories, is partially subjective ranging from 0 (no contraction) to 5 (normal strength) and not sensitive to small or moderate changes in muscle strength [19,32]. It also presents low inter-tester reliability [7,24].The hand-held dynamometer (HHD) is an objective measurement. A maximum voluntary isometric contraction measured with HHD is a rather simple, and easy accessible way to assess muscle weakness. However, previous studies pointed out a lack of inter-tester reliability and recommended not to rely only on HHD measurements for evaluation of treatment effects in patients with neurological disorders [44,46,55]. The variability comes from the difficulty to ensure an isometric contraction [55,57] and to find a standardized position [28]. Both manual testing and HHD require time and effort from the therapist and patient. Moreover, the lying or sitting postures used during these tests do not correspond to the walking posture [27]. Alternative methods may be valuable to guarantee better reliability of measurements in patients with motor disorders, save the therapist's effort, and use a standardized position closer to that of walking.

In the past two decades, conventional rehabilitation approaches have been complemented with robotic-assisted devices and especially for gait rehabilitation. The Lokomat (Hocoma, Switzerland), the most used walking robotic aid in rehabilitation [23], provides weight support and assists the patient's hip and knee efforts using four servomotors (*i.e.*, engine with torque and position sensors). These servomotors can measure torques at the hip and knee joints during maximal voluntary isometric torque (MVIT) in the so-called "L-Force" test (see reference 41 for more technical details). When performed during a Lokomat training session, it requires only 5 minutes-and allows a more common follow-up of muscle strength at an averaged joint angle of gait [25,37]. Compared to the HHD, L-Force allows for better standardization of measurement and for better stabilization during measurements by avoiding compensatory movements [8]. Moreover, L-Force tool provides real-time feedback, which is particularly valuable for motor control and motivational purposes in children with CP who often exhibit proprioceptive and attention disorders [4,35]. Despite the current use of Lokomat in gait rehabilitation [23], the L-Force tool is rarely used by clinicians due to the lack of metrological information, especially its reliability in paediatric populations. In adults with neurological disorders, Bolliger et al. [9] highlighted a sufficient inter and intra-tester reliability (ICC=0.5-0.97) of the L-Force tool for clinical use. However, to the best of our knowledge, no study has evaluated the reliability in children with CP. The purpose of the present study was to assess the reliability of the L-Force tool implemented in the paediatric orthotics of the Lokomat and the correlation with HHD measures in children with cerebral palsy. A better understanding of the reliability of this assessment method would allow a better use of the L-Force to investigate and follow up the strength gain during gait rehabilitation process in children with CP.

Material and Methods

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. Then, considering Bolliger et al. [9] study, the minimal sample size was 15 for this reliability analysis. In anticipation of possible data loss or participant attrition, 17 children with CP were included in this study. The inclusion criteria were (1) a diagnosis of spastic bilateral CP with a Gross Motor Function Classification System (GMFCS) level I, II or III [38], (2) ability to communicate fear, discomfort or pain, (3) understanding simple instructions, (4) a femur length of 23-35 cm (to fit in Lokomat pediatric orthosis) and, (5) having the degree of passive joint range of motion in the hips and knees that allowed them to assume the test position (30° hip flexion, 45° knee flexion). Children were excluded if they had a surgery within the last 12 months. Following the recruitment, the sample was composed of 9 boys and 8 girls (mean ± standard deviation, age: 10.0±3.2 years; height: 132±10 cm and mass: 30.6±9.7 kg). Ten of them were classified as GMFCS level II and 7 as level III. This study was approved by the Research Ethics Board of UHC Sainte-Justine. Written parental informed consent and child assent were also obtained.

Testing

MVIT was assessed in four muscle groups (i.e., hip flexors and extensors and knee flexors and extensors) bilaterally using L-Force tool. L-Force test was performed in a two stage protocol using the pediatric version of Lokomat Pro (Hocoma AG, Volketswil, Switzerland). HHD measurements were also taken for the same muscle groups in the same day as the inter-tester evaluation.

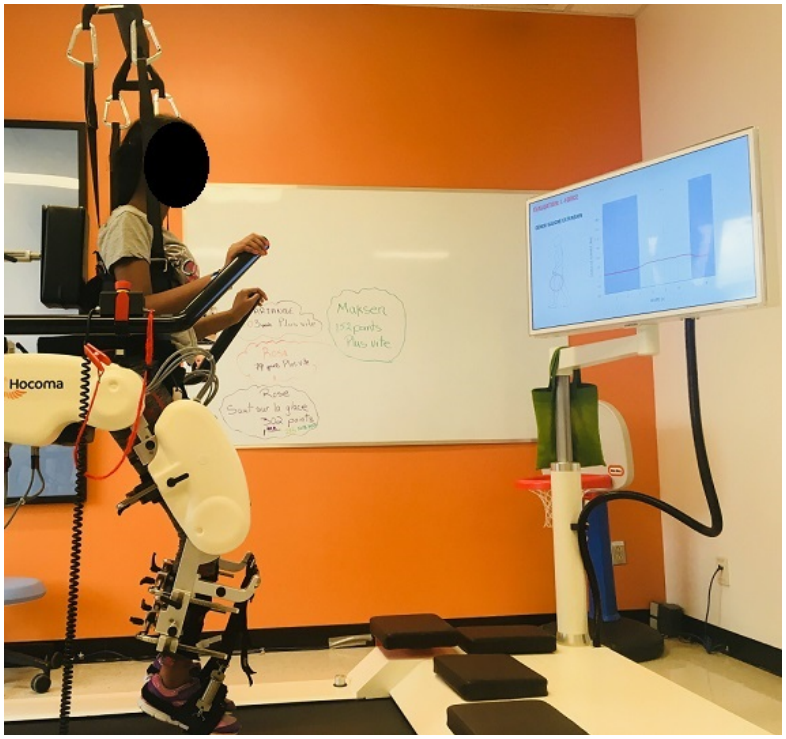

Figure 1: Subject installed in the position used for the MVIT measurement with the L-Force tool. The Lokomat is set to position control mode with preset fixed joint angles (hip 30° flexion, knee 45° flexion).

Stage 1 – Inter-tester reliability of L-Force and its correlation with the HHD

L-Force tests were performed by two experienced therapists (GG and YC). The order of the two testers was randomized and each tester was blinded to the results obtained by the other. Each participant was installed by the first tester into the Lokomat with the pre-set fixed joints angles (30° hip flexion, 45° knee flexion, **Figure 1**). Each participant accomplished a familiarization trial of L-Force test with submaximal effort followed by two maximal effort tests. During each test, the instruction "3-2-1-go" was displayed on a computer screen and was verbally given by each tester as well. Each participant was instructed to produce force as fast and as hard as possible, and was required to hold maximum strength for 5 seconds. The joint torque was measured by the Lokomat and displayed on the screen for the child and the tester. Maximum flexion and extension torques were reported for hips and knees. A 2–min rest period was allowed between trials. Then, the participant was taken out of the Lokomat and had a 5-min rest period for fatigue recovery. Thereafter, the second tester re-installed the participant into the Lokomat using the same setting of body weight support and the same pre-set fixed joint angle. She repeated the protocol in the same manner as the first tester.

One to two hours after the L-Force testing, an experienced assessor (YC) measured the maximal voluntary isometric torques using an HHD, to assess the correlation between the two measures of strength (L-Force test *vs* HHD). The HHD test positions were similar to those used by Eek et al.[21]. The participants were instructed to push as hard and as fast as possible over a 5-s period until hearing the auditory signal generated by the HHD.

Stage 2 – Intra-tester reliability of L-Force

The second stage was carried out a week later by tester GG only to assess the intra-tester reliability. Each participant was installed into the Lokomat using the same anthropometric settings as in stage 1. Then participant performed two L-Force trials with a 2-min resting period in-between.

Statistical analysis

An analysis of variance (ANOVA)-based intraclass correlation coefficients (ICC) was used to evaluate the reliability of L-Force measurements. All statistics were processed using the SPSS package (SPSS Inc., Chicago, IL, USA). To test reliability, we calculated ICCs with 95% confidence intervals (two-way random-effects model) by using both single values (in each case the maximal measurement of testers G and Y) and average values (average of measurements for each joint in every direction). ICC scores were compared with the following scale for interpretation of correlation: excellent (1.00 – 0.8), good (0.80 – 0.60), and poor (< 0.60) [56]. Bland-Altman plots were also reported to describe the level of agreement between intra and inter-tester measurements [5]. Additionally, the absolute standard error of measurement (SEM) in unit of joint torque, the relative SEM in percentage of grand mean and the coefficient of variation (CV) were calculated. While the ICC reflects the degree of consistency of a measurement and is unit free, the SEM and the CV provides information about the expected trial-to-trial noise in the measured data. Correlations between L-Force and HHD measures were determined by using the Pearson score ($r < 0.20$, "very weak"; 0.20–0.39, "weak"; 0.40–0.59, "moderate"; 0.60–0.79, "strong" and 0.80–1.00 "very strong relationship) [56]. The significance level was set to $p=0.05$. As it is recognized that there are large inter-limb strength differences in children with CP, statistical analysis considered each side independently for all the tests (n=2x17), as done in previous studies [42,43,52,54].

Results

Part 1: Reliability of L-Force measurements

The means and standard deviations of measured muscle strength for the three evaluations are reported in **Table 2**. For inter-tester reliability, ICCs ranged from 0.80 to 0.87 and SEM from 2.1 to 3.5 Nm (i.e., 12.1 - 21.7%). As for intra-tester reliability, ICCs ranged from 0.70 to 0.87 while the SEM varied from 2.0 to 4.1 Nm (i.e., 11.9 - 22.5%). The highest SEM value was observed in hip extension for both intra and inter-tester assessments (4.1 and 3.5 Nm, respectively).

Reliability was good for all ICCs calculated from single as well as from averaged measures (see **Table 3**). Bland-Altman plots were reported as supplementary material (see **Figures S1 and S2).**

Table 1: Maximal voluntary isometric contraction (Nm) in 17 patients with cerebral palsy. Data are mean (standard deviation) of the maximal voluntary isometric contraction strength as measured by tester GG (twice) and by tester YC (once) using L-Force tool

Joint	**Tester GG (stage 1)**	**Tester GG (stage 2)**	**Tester YC (stage 1)**
Hip flexion	19.05 (11.2)	20.8 (11.2)	18.8 (10.3)
Hip extension	16.6 (13.4)	19.9 (15.6)	17.6 (12.2)
Knee flexion	10.7 (8.0)	10.5 (8.8)	9.0 (7.0)
Knee extension	9.2 (8.3)	10.7 (8.2)	10.5 (8.5)

Table 2: Inter and intra-tester reliability of L-Force measurements in hip and knee flexion and extension (All, p≤0.001)

	Inter-tester					Intra-tester				
Joint	**Single measurement ICC (CI 95%)**	**Average measurement ICC (CI 95%)**	**SEM (Nm)**	**SEM (%)**	**CV (%)**	**Single measurement ICC (CI 95%)**	**Average measurement ICC (CI 95%)**	**SEM (Nm)**	**SEM (%)**	**CV (%)**
Hip flexion	0.80 (0.63-0.89)	0.89 (0.77-0.94)	2.3	12.1	14	0.87 (0.76-0.94)	0.93 (0.86-0.97)	2.3	11.9	13
Hip extension	0.87 (0.75-0.93)	0.93 (0.86-0.96)	3.5	20.6	22	0.86 (0.70-0,93)	0.92 (0.83-0.96)	4.1	22.5	24
Knee flexion	0.80 (0.62-0.89)	0.89 (0.76-0.94)	2.1	21.6	26	0.79 (0.62-0.89)	0.88 (0.76-0.94)	2.1	20.0	24
Knee extension	0.85 (0.72-0.92)	0.92 (0.84-0.96)	2.1	21.7	25	0.70 (0.49-0.91)	0.83 (0.66-0.91)	2.0	19.6	25

ICC: Intraclass correlation coefficient; SEM: standard error of measurement; CV: coefficient of variation; CI: confidence interval.

Part 2: Correlations between L-Force and HHD measurements

All correlations were positive and significant between L-Force and HHD measures (see **Figure 4**). For the hip and knee flexors, the correlations were equal to 0.769 and 0.609 (p≤0.001) respectively, which indicates the presence of a strong relationship between the L-Force and the HHD. However, the correlations were moderate for hip and knee extensors (r=0.530 and 0.528, p≤0.001).

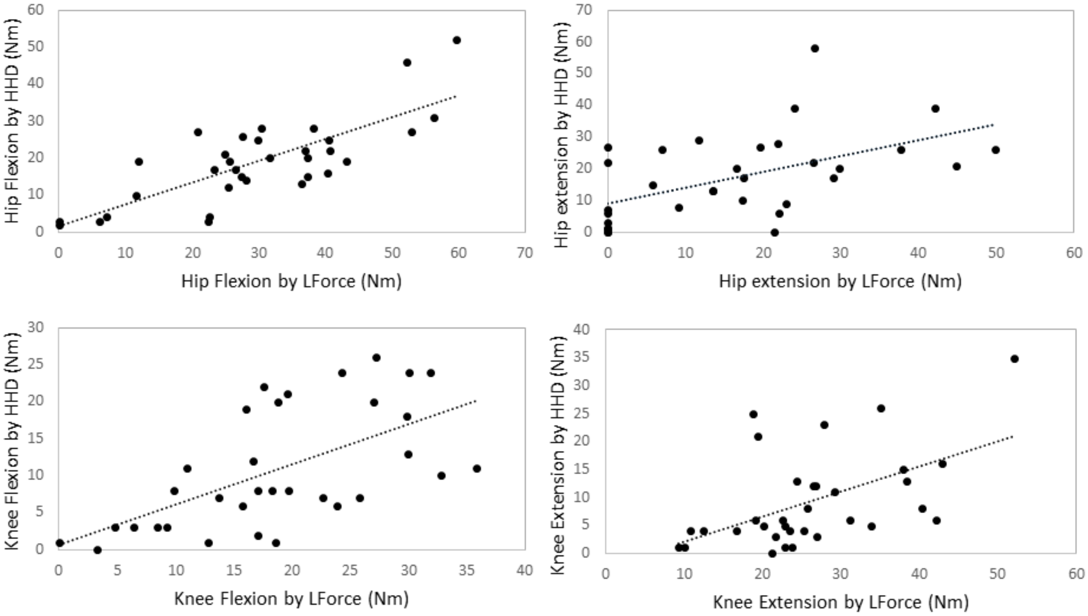

Figure 2: Scatter plots of MVITs measured by the HHD and L-Force.

Discussion

The purpose of this study was to assess the reliability of Lokomat-based tool (L-Force) to measure maximal voluntary isometric torque in CP children (GMFCS levels II and III). Our main findings were that (1) inter and intra-reliability were good to excellent for both knee and hip in flexion and extension; and that (2) the L-Force measures were more correlated with HHD in flexion than in extension.

In healthy adults, L-Force presents good to excellent intra-tester (ICC=0.71-0.90) and inter-tester reliability (ICC=0.72-0.95) [9], which are better than those found with HHD in the same population [46]. Fair to excellent reliability of L-Force were also found in adults with neuromuscular disorders (ICC=0.50-0.96 for intra-tester and 0.66-0.97 for inter-tester) [9]. In the paediatric CP population, the present study reported good to excellent reliability (ICC= 0.80-0.87 in inter-tester and 0.70-0.87 in intra-tester). Again, inter-reliability coefficients were better than those obtained with the HHD in children with CP (n=25) when compared to Verschuren et al. [55] results. They reported an ICC value ranging from 0.42 to 0.73 for the break-method (which requires that the examiner pushes against the child's limb until the subject's maximal muscular effort is overcome and the joint being tested gives way), and from 0.49 to 0.82 for the make-method (the child is instructed to push as hard as possible against the HHD that is maintained perpendicular to the child's limb segment) [55]. The tester's strength is a major determinant of the inter-tester reliability with HHD [57]. This source of variability disappears with the fixed support offered by the Lokomat. Moreover, all patients are tested in a standardized position in the Lokomat, as close as possible to the walking posture. It is harder to standardized positions when using the HHD with children with spastic CP because compensatory movements during the measurements cannot be excluded [3,55]. Because of the force-length relationship of mono- and bi-articular muscles [1], the different postures between L-Force and HHD would explain the measurement differences between these two tools. The L-Force tool could be in line with the contemporary task-oriented approach because it allows to evaluate MVITs at an averaged joint angle of gait. Such evaluation should help to refine the relationship between muscle strength and walking abilities. Future studies should evaluate if L-Force measures are more correlated with static tasks and walking abilities than HHD measures, done with hip and knee flexed at 90° [25,40].We found better inter-tester coefficients than intra-tester coefficients which is in agreement with previous findings [9]. Both studies determined the inter-tester reliability the same day while measurements for estimating the intra-tester reliability were spaced a few days apart. This finding is consistent with the fact that children with CP showed a large day to day variability in the generation of muscle force [50]. As in adult with neuromuscular disorders, L-Force is a reliable tool to assess the muscle status in a group of children with CP, which seems to outperform the HHD.

SEM is the most clinically relevant metric since it facilitates the interpretation of whether changes (e.g., caused by an intervention) exceed measurement error or not [16]. A direct comparison with adult populations [9] is not possible since authors did not report relative SEM (%) and comparison of absolute SEM is irrelevant due to the large difference in muscle strength. However, our absolute SEM values were overall smaller than those reported with HHD in children with cerebral palsy [50,55]. These differences are certainly due to the reduced uncertainty obtained with the L-Force tool and might also be due to using test positions which are standardized. In agreement with Bolliger et al. [9], the lowest SEM was observed for the hip flexors (12% in both intra and inter-testers measures) and the highest SEM for the hip extensors (22% in intra-tester tests). This is consistent with the prominent weakness in lower limb extensors often observed in patients with CP [15]. Moreover, this variability could also be caused by intrinsic factors (as muscle tone variability, muscles co-contraction and fatigue). Although the co-contraction phenomenon has been mainly described as a protective mechanism at a joint [2], the amount of antagonist co-contraction could also significantly influence the resultant torque

[10,39]. Finally, a source of variability can also come from the complexity of the task (i.e., the ability to isolate selected muscle activation), especially in children with CP who present a poor selective motor control [48].

There is a strong relationship between muscle strength and walking abilities [13,20]. To interpret the effectiveness of interventions, longitudinal changes should then be compared with SEM values. In adults with neurologic disorders, studies assessing the effects of training have shown improvements of 43–58% in maximal voluntary isometric torque [11,12], . Besides, in children with CP, some studies reported an increase of 30–80% in lower limb muscle strength following 4 to 12 weeks of training [6,14,22,36]. Compared to our SEM (%) values, the L-Force tool represents a reliable indicator in interventional studies to detect the real benefit of training in a population that resembles our study sample (i.e., GMFCS levels II–III). Furthermore, regular follow-ups with the L-Force tool should help to determine/adjust the duration of training that could be expected to improve strength. Training duration and frequency are ongoing topics in clinical research and are still to some extent controversial. In his systematic review, Scianni et al. [45] reported changes in muscle strength after 4 to 16 weeks of training in children with CP. The results of 16 weeks of training were similar and sometimes lower than those obtained with 4 to 8 weeks of training. This means that longer interventions are not necessarily more effective [6,14,17,29,53]. It is thus more appropriate to follow-up more frequently on muscle strength changes during training (e.g. every 1 or 2 weeks) so that these changes can be detected earlier and interventions made more effective. The L-Force assessment tool is a reliable approach to evaluate muscle strength in a group of children with cerebral palsy (i.e., GMFCS II and III) in a walking posture. Hence, this tool should allow walking-specific strength assessments and could be used to clarify the relationship between walking abilities and lower limb muscle strength.

A few limitations can be evoked in this study. First, the results are valid for CP children with GMFCS level II and III by considering the same inclusion/exclusion criteria of this study. These results cannot be generalized to children with lower functional levels or with other clinical subtypes of CP. Second, cognition impairment was not formally assessed, while it has been cited as a possible reason for large within participant variability when assessing muscle strength in children with CP [45]. Third, the intra and inter-tester performances can be influenced by the way the child is installed in the Lokomat as well as the motivation or co-operation of the patient that may differ according to the day and the tester. Indeed, fatigue and boredom can be observed in this kind of experimental protocol and undermine the reliability of measurements [49]. Fourth, measuring muscle strength in L-Force position may be uncomfortable. Fifth, the high costs of a Lokomat limit the use of the L-Force tool to rehabilitation centers that already own this device. Finally, to date, the clinical usage of L-Force is limited to children who receive gait training with the Lokomat.

Conclusion

The good to excellent inter and intra-tester reliability of the L-Force supports its use in the follow-ups in children with cerebral palsy with GMFCS levels II and III. To analyze changes in muscle strength, we recommend using our relative SEM values to determine if the change is within uncertainties or not, and to consider each muscle group separately.

Acknowledgements

The authors are grateful for the help of the Ordre professionnel de la physiothérapie du Québec (OPPQ) which funded this study. The first author is scholar of Quebec Research Fund - Nature and Technology (FRQ-NT). In addition, the children, their parents, and the (paediatric) physical therapists from the UHC Sainte-Justine (Marie Enfant Rehabilitation Center and affiliated schools) who gave their assistance are appreciated. The authors appreciate the invaluable assistance of Clara Ziane (Université de Montréal) for her expert review of the article in the English language.

Disclosure of interest

The authors declare that they have no competing interest.

References

[1] Arnold EM, Hamner SR, Seth A, Millard M, Delp SL. How muscle fiber lengths and velocities affect muscle force generation as humans walk and run at different speeds. J Exp Biol 2013;216:2150–60.

[2] Baratta R, Solomonow M, Zhou BH, Letson D, Chuinard R, D'Ambrosia R. Muscular coactivation. The role of the antagonist musculature in maintaining knee stability. Am J Sports Med 1988;16:113–9.

[3] Berry ET, Giuliani CA, Damiano DL. Intrasession and intersession reliability of handheld dynamometry in children with cerebral palsy. Pediatr Phys Ther 2004;16:191–7.

[4] Beunen G, Thomis M. Muscular Strength Development in Children and Adolescents. Pediatr Exerc Sci 2000;12:174–97.

[5] Bland JM, Altman DG. Measuring agreement in method comparison studies. Stat Methods Med Res 1999;8:135–60.

[6] Blundell SW, Shepherd RB, Dean CM, Adams RD, Cahill BM. Functional strength training in cerebral palsy: a pilot study of a group circuit training class for children aged 4-8 years. Clin Rehabil 2003;17:48–9.

[7] Bohannon RW. Manual muscle testing: does it meet the standards of an adequate screening test? Clin Rehabil 2005;19:662–5.

[8] Bohannon RW. Minimal detectable change of knee extension force measurements obtained by handheld dynamometry from older patients in 2 settings. J Geriatr Phys Ther 2012;35:79–81.

[9] Bolliger M, Banz R, Dietz V, Lünenburger L. Standardized voluntary force measurement in a lower extremity rehabilitation robot. J Neuroengineering Rehabil 2008;5:23-8.

[10] Buckon CE, Thomas SS, Harris GE, Piatt JH, Aiona MD, Sussman MD. Objective measurement of muscle strength in children with spastic diplegia after selective dorsal rhizotomy. Arch Phys Med Rehabil 2002;83:454–6.

[11] Cherni Y, Begon M, Chababe H, Moissenet F. Use of electromyography to optimize Lokomat(®) settings for subject-specific gait rehabilitation in post-stroke hemiparetic patients: A proof-of-concept study. Neurophysiol Clin 2017;47:293–6.

[12] Cramp MC, Greenwood RJ, Gill M, Rothwell JC, Scott OM. Low intensity strength training for ambulatory stroke patients. Disabil Rehabil 2006;28:883–6.

[13] Dallmeijer AJ, Rameckers EA, Houdijk H, de Groot S, Scholtes VA, Becher JG. Isometric muscle strength and mobility capacity in children with cerebral palsy. Disabil Rehabil 2017;39:135–7.

[14] Damiano DL, Abel MF. Functional outcomes of strength training in spastic cerebral palsy. Arch Phys Med Rehabil 1998;79:119–25.

[15] Damiano DL, Arnold AS, Steele KM, Delp SL. Can Strength Training Predictably Improve Gait Kinematics? A Pilot Study on the Effects of Hip and Knee Extensor Strengthening on Lower-Extremity Alignment in Cerebral Palsy. Phys Ther 2010;90:269–79.

[16] de Vet HCW, Terwee CB, Knol DL, Bouter LM. When to use agreement versus reliability measures. J Clin Epidemiol 2006;59:1033–6.

[17] Dodd KJ, Taylor NF, Damiano DL. A systematic review of the effectiveness of strength-training programs for people with cerebral palsy. Arch Phys Med Rehabil 2002;83:1157–64.

[18] Dodd KJ, Taylor NF, Graham HK. A randomized clinical trial of strength training in young people with cerebral palsy. Dev Med Child Neurol 2003;45:652–5.

[19] Dvir Z. Grade 4 in manual muscle testing: the problem with submaximal strength assessment. Clin Rehabil 1997;11:36–41.

[20] Eek M, Beckung E. Walking ability is related to muscle strength in children with cerebral palsy. Gait Posture 2008;28:366–71.

[21] Eek MN, Kroksmark A-K, Beckung E. Isometric muscle torque in children 5 to 15 years of age: normative data. Arch Phys Med Rehabil 2006;87:1091–8.

[22] Faigenbaum AD. State of the Art Reviews: Resistance Training for Children and Adolescents: Are There Health Outcomes? Am J Lifestyle Med 2007;1:190–1.

[23] Fisahn C, Aach M, Jansen O, Moisi M, Mayadev A, Pagarigan KT, et al. The Effectiveness and Safety of Exoskeletons as Assistive and Rehabilitation Devices in the Treatment of Neurologic Gait Disorders in Patients with Spinal Cord Injury: A Systematic Review. Glob Spine J 2016;6:822–41.

[24] Frese E, Brown M, Norton BJ. Clinical reliability of manual muscle testing. Middle trapezius and gluteus medius muscles. Phys Ther 1987;67:1072–4.

[25] Goudriaan M, Nieuwenhuys A, Schless S-H, Goemans N, Molenaers G, Desloovere K. A new strength assessment to evaluate the association between muscle weakness and gait pathology in children with cerebral palsy. PloS One 2018;13:e0191097.

[26] Gregson JM, Leathley MJ, Moore AP, Smith TL, Sharma AK, Watkins CL. Reliability of measurements of muscle tone and muscle power in stroke patients. Age Ageing 2000;29:223–5.

[27] Hébert LJ, Maltais DB, Lepage C, Saulnier J, Crête M, Perron M. Isometric muscle strength in youth assessed by hand-held dynamometry: a feasibility, reliability, and validity study. Pediatr Phys Ther 2011;23:289–99.

[28] Jones M, Stratton G. Muscle function assessment in children. Acta Paediatr 2000;89:753-8.

[29] Kerr C, McDowell B, Cosgrove A, Walsh D, Bradbury I, McDonough S. Electrical stimulation in cerebral palsy: a randomized controlled trial. Dev Med Child Neurol 2006;48:870–6.

[30] Kim CM, Eng JJ, Whittaker MW. Level walking and ambulatory capacity in persons with incomplete spinal cord injury: relationship with muscle strength. Spinal Cord 2004;42:156–62.

[31] Leonard CT, Stephens JU, Stroppel SL. Assessing the spastic condition of individuals with upper motoneuron involvement: validity of the myotonometer. Arch Phys Med Rehabil 2001;82:1416–20.

[32] Li RC, Jasiewicz JM, Middleton J, Condie P, Barriskill A, Hebnes H, et al. The development, validity, and reliability of a manual muscle testing device with integrated limb position sensors. Arch Phys Med Rehabil 2006;87:411–6.

[34] Marino RJ, Graves DE. Metric properties of the ASIA motor score: subscales improve correlation with functional activities. Arch Phys Med Rehabil 2004;85:1804–6.

[35]. Michaud B, Cherni Y, Begon M, Girardin-Vignola G, Roussel P. A serious game for gait rehabilitation with the Lokomat. In: 2017 International Conference on Virtual Rehabilitation (ICVR); 2017.

[36] Morton JF, Brownlee M, McFadyen AK. The effects of progressive resistance training for children with cerebral palsy. Clin Rehabil 2005;19:283–6.

[37] Nieuwenhuys A, Papageorgiou E, Pataky T, Laet TD, Molenaers G, Desloovere K. Literature Review and Comparison of Two Statistical Methods to Evaluate the Effect of Botulinum Toxin Treatment on Gait in Children with Cerebral Palsy. PLoS One 2016;11:e0152697.

[38] Palisano RJ, Rosenbaum P, Bartlett D, Livingston MH. Content validity of the expanded and revised Gross Motor Function Classification System. Dev Med Child Neurol 2008;50:744–6.

[39] Patton NJ, Mortensen OA. An electromyographic study of reciprocal activity of muscles. Anat Rec 1971;170:255–68.

[40] Ploutz-Snyder LL, Manini T, Ploutz-Snyder RJ, Wolf DA. Functionally relevant thresholds of quadriceps femoris strength. J Gerontol A Biol Sci Med Sci 2002;57:144-8.

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

[42] Sangeux M, Rodda J, Graham HK. Sagittal gait patterns in cerebral palsy: the plantarflexor-knee extension couple index. Gait Posture 2015;41:586–91.

[43] Sangeux M, Wolfe R, Graham HK. One side or two? Dev Med Child Neurol 2013;55:786–7.

[44] Schrama PPM, Stenneberg MS, Lucas C, van Trijffel E. Intraexaminer reliability of hand-held dynamometry in the upper extremity: a systematic review. Arch Phys Med Rehabil 2014;95:2444–69.

[45] Scianni A, Butler JM, Ada L, Teixeira-Salmela LF. Muscle strengthening is not effective in children and adolescents with cerebral palsy: a systematic review. Aust J Physiother 2009;55:81–7.

[46] Scott DA, Bond EQ, Sisto SA, Nadler SF. The intra- and interrater reliability of hip muscle strength assessments using a handheld versus a portable dynamometer anchoring station. Arch Phys Med Rehabil 2004;85:598–603.

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

[48] Smits DW, Ketelaar M, Gorter J.W, van Schie P, Dallmeijer A, Jongmans M, et al. Development of daily activities in school-age children with cerebral palsy. Res Dev Disabil 2011;32:222–34.

[49] Stackhouse SK, Binder-Macleod SA, Lee SCK. Voluntary muscle activation, contractile propreties and fatigability in children with and without cerebral palsy. Muscle Nerve 2005;31:594–7.

[50] Taylor NF, Dodd KJ, Graham HK. Test-retest reliability of hand-held dynamometric strength testing in young people with cerebral palsy. Arch Phys Med Rehabil 2004;85:77–80.

[50] Valvano J, Newell KM. Practice of a precision isometric grip-force task by children with spastic cerebral palsy. Dev Med Child Neurol 1998;40:464–9.

[51] van den Berg-Emons RJ, van Baak MA, de Barbanson DC, Speth L, Saris WH. Reliability of tests to determine peak aerobic power, anaerobic power and isokinetic muscle strength in children with spastic cerebral palsy. Dev Med Child Neurol 1996;38:1117–8.

[52] 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.

[53] van der Linden ML, Hazlewood ME, Aitchison AM, Hillman SJ, Robb JE. Electrical stimulation of gluteus maximus in children with cerebral palsy: effects on gait characteristics and muscle strength. Dev Med Child Neurol 2003;45:385–5.

[54] van der Linden ML, Hazlewood ME, Hillman SJ, Robb JE. Passive and dynamic rotation of the lower limbs in children with diplegic cerebral palsy. Dev Med Child Neurol 2006;48:176–80.

[55] Verschuren O, Ketelaar M, Takken T, Van Brussel M, Helders PJM, Gorter JW. Reliability of hand-held dynamometry and functional strength tests for the lower extremity in children with Cerebral Palsy. Disabil Rehabil 2008;30:1358–66.

[56]. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res 2005;19:231–9.

[57] Wikholm JB, Bohannon RW. Hand-held Dynamometer Measurements: Tester Strength Makes a Difference. J Orthop Sports Phys Ther 1991;13:191–8.

Supplementary materials

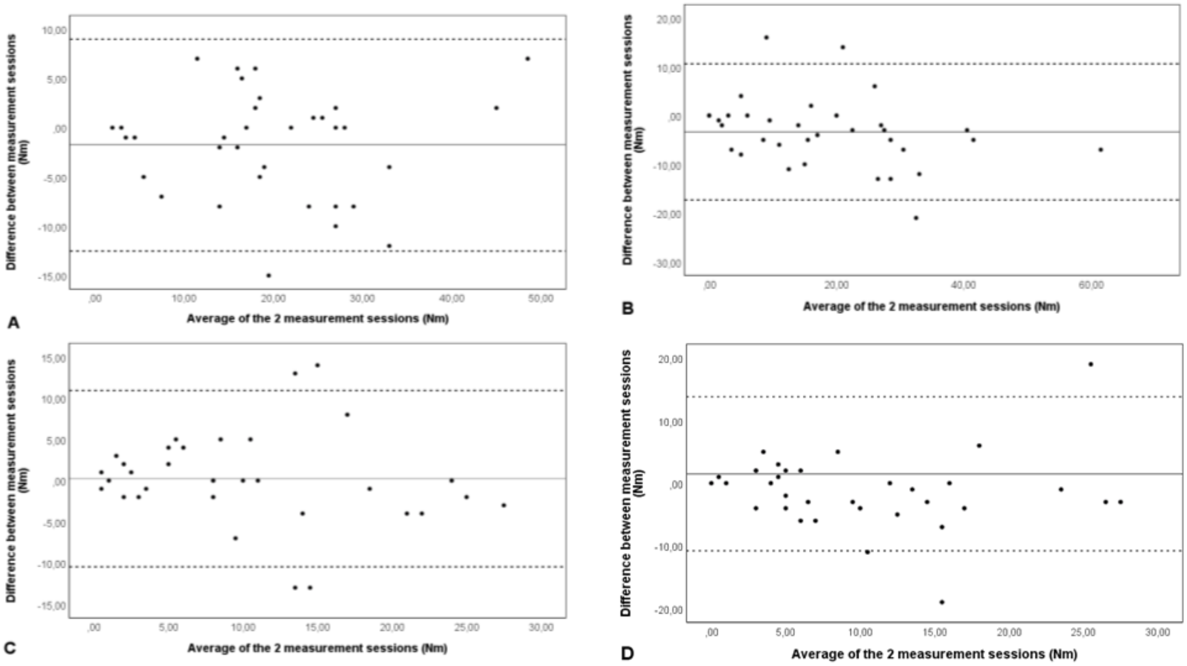

Figure S1: Intra-tester Bland and Altman plots depict the differences between MVIT measured by tester GG in session 1 and MVIT measured by tester GG in session 2 against the average values (filled lines), with 95% limits of agreement (broken lines). (A) Hip flexion MVIT; (B) Hip extension MVIT; (C) Knee flexion MVIT; and (D) Knee extension MVIT.

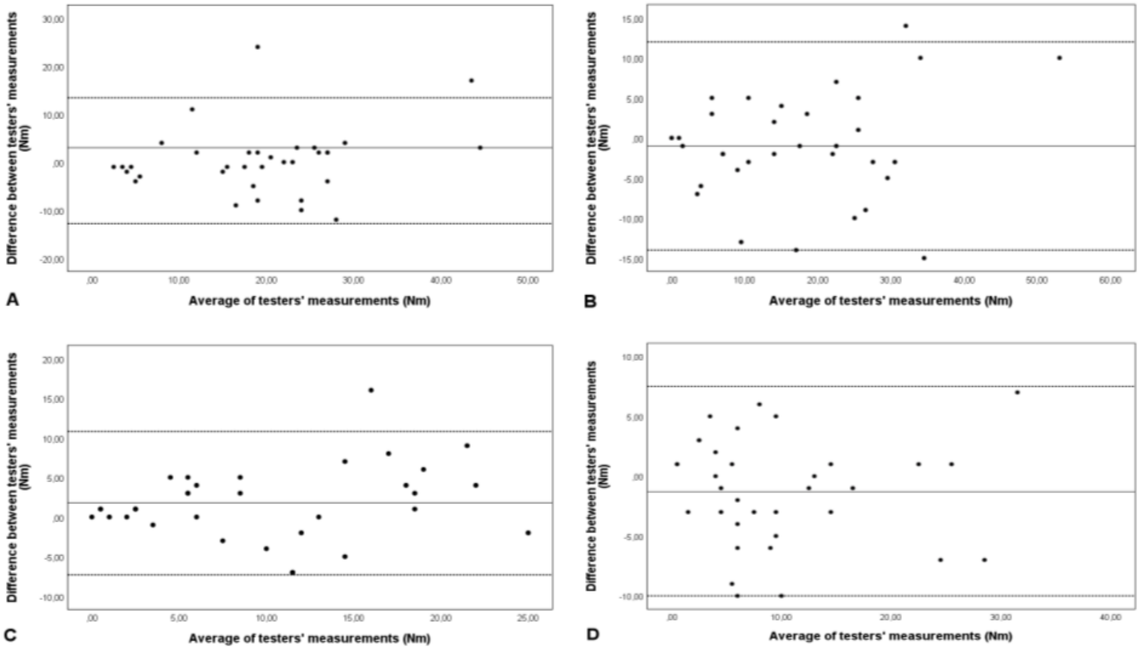

Figure S2: Inter-tester Bland and Altman plots depict the differences between measurement of tester GG and tester YC against the average values (filled lines), with 95% limits of agreement (broken lines). (A) Hip flexion MVIT; (B) Hip extension MVIT; (C) Knee flexion MVIT; and (D) Knee extension MVIT.