OPEN

RESEARCH ARTICLE

Hand-Held Dynamometry Isometric Torque Reference Values for Children and Adolescents

Luc J. Hébert, PT, PhD; Désirée B. Maltais, PT, PhD; Céline Lepage, PT, MSc; Joanne Saulnier, PT; Mélanie Crête, PT

Rehabilitation Department (Dr Hébert and Maltais), and Radiology Department (Dr Hébert), Laval University, Quebec City, Quebec, Canada; Centre for Interdisciplinary Research in Rehabilitation and Social Integration (Drs Hébert and Maltais), Quebec, Canada; and Quebec Rehabilitation Centre (Mss Lepage, Saulnier and Crête), Quebec City, Quebec, Canada.

Purpose: To establish hand-held dynamometry (HHD) maximal isometric muscle torque (MIT) reference values for children and adolescents who are developing typically. **Methods:** The MIT of 10 upper and lower limb muscle groups was assessed in 351 Caucasian youth (4 years 2 months to 17 years) using a standardized HHD protocol, previously shown to be feasible, valid, and reliable. **Results:** The mean MIT and 95% confidence interval of the mean for all muscle groups, for each of the 14 age groups (1 year age span for each group), and for each sex, were reported in both absolute (Nm) and normalized (Nm/kg) values. **Conclusion:** These HHD reference values may be helpful in the identification of muscle strength impairments in several pediatric populations, especially when bilateral impairments are present. **(Pediatr Phys Ther 2015;27:414–423)** *Key words: adolescent, age factors, child, lower limbs, muscle strength dynamometer, reference values, sex factors, upper limbs*

INTRODUCTION AND PURPOSE

Muscle strength is an important clinical measure in pediatric rehabilitation. Limitations in walking, running, and rising to standing, for example, are related to muscle strength in several different clinical groups.[1-7] Moreover, physical capacity as measured using standardized clinical tests has been shown to improve with improvements in muscle strength.[3,4,8]

0898-5669/110/2704-0414
Pediatric Physical Therapy

Correspondence: Luc J. Hébert, PT, PhD, Rehabilitation Department (Physiotherapy), and Radiology Department, Laval University, and Centre for Interdisciplinary Research in Rehabilitation and Social Integration, CIRRIS-IRDPQ, Rm H-1702, 525, Blvd Wilfrid-Hamel, Quebec, QC G1M 2S8, Canada (ljherbert@vidotron.ca).

The authors declare no conflicts of interest.

This research was supported by a grant from the Fondation Élan of the Quebec Rehabilitation Centre, and a grant from the Réseau Provincial de Recherche en Adaptation-Réadaptation (REPAR).

DOI: 10.1097/PEP.0000000000000179

Since children with physical disabilities often have bilateral impairments, a comparison muscle group "outside of the person" may be necessary to identify muscle weakness.[9] This implies the use of reference data in the absence of true normative values. Since muscle strength increases with growth and maturation, these types of data may also provide information on the extent of, or changes in, the strength impairment that cannot be detected by simply comparing strength values for the same individual over time. For reference values to be useful in clinical decision making, however, they need to be obtained using methods that are clinically feasible and that yield valid and reliable data, such as hand-held dynamometry (HHD).[2,11-17] Other methods commonly used in the clinic or in research have limitations that render them less useful in clinical decision making. For example, manual muscle testing, while clinically feasible, often has problems with validity because of the subjectivity of the grading system.[4,10,11] Isokinetic dynamometry, a method with sound psychometric properties that is frequently used in research, is often not clinically feasible because the equipment is costly and requires user training and space for housing. It may also require additional specific mechanical arm segments for children, and some adolescents as their limbs are often too short to fit the standard arm segments that are typically provided with this type of equipment. Given limitations of manual muscle testing and constraints of isokinetic equipment, HHD has emerged as a promising alternative to these other methods for muscle strength evaluation in the clinic.[2,11-17]

Only a few studies, however, have established reference strength data using HHD in youth, and the reference values published to date have several limitations.[9,18-25] No single protocol has been used to evaluate muscle strength across a wide age range. To obtain values for youth between 3.5 and 18 years, one needs to go to several different articles that used different HHD protocols. This means it can be difficult to separate real differences in strength from differences due to the protocol. As well, strength values are often reported as force in kg or Newtons and not as torque in Newton-meters.[18-22,24] This means the effect of height differences (or lever arm differences) on muscle strength is not completely accounted for. The number of participants per age group for existing reference data is also small.[9,18,21,24,25] In addition, some of the testing positions used to derive these values are not feasible for certain clinical populations as they require effort against gravity or they have insufficient stabilization.[9,18-21,24] The choice of equipment or test used for some existing reference data is also inappropriate (eg, measuring strength using an HHD with a spring-loaded cell, the use of a break test or a 1-repetition maximum, HHD protocols with poor ergonomic or stabilization procedures).[18,20,22,24,25] For other reference data in the literature, the validity of the values is questionable because the maximal force that can be validly measured with an HHD for the target muscle group is below its maximum isometric force.[9,18,21] Prediction equations available in the literature are also limited, mainly because of large standard errors due to small sample sizes or a failure to take into account all the predictor or confounding variables.[9,19,20,24]

We have recently developed a HHD protocol to assess maximal isometric torque (MIT) in several upper and lower limbs muscle groups for children and adolescents 4 to 17.5 years old.[26] The protocol is feasible over this age range and MIT values for youth who are developing typically are valid and reliable.[27] More specifically, the mean concurrent validity (intraclass correlation coefficient [ICC]) of these MIT values with values measured using a Cybex isokinetic dynamometer varies from 0.78 to 0.93 (depending on the muscle group) with the exception of ankle plantar flexors (ICC = 0.48).[27] The intra- and interrater ICCs for reliability vary from 0.70 to 0.98, again depending on the muscle group.[27] The main objective of this study was to establish, using our standardized HHD protocol, MIT reference values for children and adolescents who are developing typically, for 10 muscle groups of the upper (shoulder abductors and external rotators; elbow flexors and extensors) and lower (hip abductors, flexors, and extensors; knee flexors and extensors; ankle dorsiflexors) limbs. We elected to establish reference values, as a first step, with the understanding that normative values are the standard for establishing strength deficits and that reference values can at best give only an estimate of strength deficits. The secondary study objectives were (1) to compare the variations of torque between absolute and reference values, and (2) to compare the profiles of muscle strength progression between boys and girls, across age groups, and between upper and lower limbs.

METHODS

Participants

A random, probabilistic sample of 4- to 17-year-old youth who were healthy, developing typically, white and French speaking, living in a medium-sized (population of 150 000-400 000) North American city with medium socioeconomic status was established from lists from private and public daycare, elementary and secondary school classes. The participants recruited for the study were all volunteers who had accepted the offer to participate transmitted to them and their parents via daycare, primary and high school staff. Potential participants were included if they were able to take part in muscle strength assessment by HHD. They were excluded if they had a history of medical, neurological, or musculoskeletal impairments that could affect torque measurements, documented trauma in the 12 months prior to the study, or if they were taking medication or participating in competitive sports during the time of the study. Written informed consent was obtained from the parents, with assent obtained from the participants. The study was approved by the administering institution's ethics review board and by the school boards involved.

Instrumentation and Procedures

The maximum isometric muscle strength of the hip flexors, extensors and abductors, knee flexors and extensors, ankle dorsiflexors, shoulder abductors and external rotators, and elbow flexors and extensors was assessed with a recently calibrated Chatillon push-pull HHD (FCE-500, Ametek TCI Division, Chatillon Force Measurement Systems, Largo, Florida). The dynamometer was cross-calibrated with reference weights in both the compression (push technique) and distraction (pull technique) modes. The standardized positions and HHD placement for each muscle group tested are described in detail in the Appendix. As noted above, the protocol has established feasibility, validity, and reliability.[27] An antislip surface was placed under the person being evaluated during all tests.

A "make" test was used. For a make test, the examiner holds the HHD stationary, whereas the participant exerts a maximal force against it. This ensures isometric contraction. A make test was chosen over a break test because break tests have questionable reliability for measuring muscle strength using HHD for most muscle groups and the procedure puts children at a higher risk of injuries than a make test.[17,28] When using make tests with muscles that exert a large force, however, the examiner may "unconsciously" exert a counterforce that is slightly higher than the tested muscle's force. This creates a quasi break test condition, that is, a nonisometric muscle contraction. To prevent this from happening, our protocol uses the distraction mode or pull technique for muscle groups that are particularly strong (hip flexors and extensors). With this mode, a nonelastic strap is used between the thigh segment and the hook of the dynamometer so that resistance can be in a "pulling" direction. Use of the strap also provides more stability to the examiner and allows him or her to resist much higher forces than the individual would otherwise be able to do. For all other muscle groups, our protocol uses the compression mode. When developing this protocol, we also found that extra leg stabilization was needed when evaluating knee extensor MIT. For this muscle group, the participant sits at the edge of the evaluation table. The dynamometer is inserted between the anterior surface of the leg and the strap, with the strap itself attached to the leg of the table. The strap is also tightened to ensure 90° of knee flexion. In this way, the leg is well stabilized and the strap resists the isometric knee extension during the test, which minimizes examiner effort. The following factors are also standardized with our protocol[27]: (1) the verbal instructions provided before testing, (2) the verbal encouragements given during the testing, including the tone of voice and choice of words, (3) the position of both the experimenter and the participant (see Table 1 of Hébert et al[27]), (4) the position of the dynamometer and its accessories, (5) the order of the muscles tested, and (6) the execution of the tasks by the participant.

Six physiotherapists (2 per school) took the measures. The physiotherapists had received standardized, 3-day training (available from the College of Physiotherapists of Quebec-OPPQ, ISBN 2-9809219-1-2, the 3rd ed, ISBN 2-9809219-2-0). On the basis of prestudy testing, the evaluators for this study showed very good reliability with ICCs varying from 0.84 to 0.98 (intrarater) and from 0.81 to 0.96 (interrater). All measures were taken during 1 testing session. Both legs were assessed in the older participants. For those 4 to 8.5 years of age, only 1 side (randomly determined) was assessed because of their limited endurance. For all muscle groups, 3 trials per side were completed. The peak force was recorded for each trial. The mean of the 3 trials was used for the analyses. Before each trial, the participant performed 2, submaximal contractions of about 50% maximal effort. This was done as a warm-up and to ensure that the task was well understood and that stabilization was adequate. Each contraction was progressive and was held 10 seconds followed by a 60-second rest period. Height and weight measurements were done prior to the strength testing using a medical scale and height measurement system. The most common method of accounting for lower limb muscle strength differences related to body size (and not muscle weakness per se) is to divide the muscle force or torque values by the individual's body mass.[29,30] This approach was used in this study.

Study Design and Data Collection

This was a descriptive study in which a specific number ($n = 364$) of children and adolescents were recruited. This sample size was based on the statistic of the standard width of the confidence interval (CI), where W represents the total width of the CI and S the standard deviation (SD).[31] The following formula was used: $N = 4z\alpha'^2S^2/W^2$, where $z\alpha' = 1.96$ when $\alpha = .05$, $S = 6.7$ (highest SD obtained in our previous study) and $W = 8$ (largest 95% CI obtained from our previous study).[27] From a clinical standpoint, the width of a 95% CI is important as it indicates the range within which one can be 95% certain that the true effect lies. Our calculations showed that we required 10.8 participants per sex per age group. We added 15% more participants in case of data loss for a total of 12.4 participants per age group per sex, which we rounded to 13 per group (age and sex). We therefore recruited an equal number of girls and boys (13 girls and 13 boys) for each of the 14 different age groups in this study, from 4 years to 17 years of age.

Data Analysis

The Kolmogorov-Smirnov and the Shapiro-Wilk tests of normality were performed for each muscle group's torque data ($n = 354$) (pooled for age). Data were considered to be outliers (and thus removed) when they were greater than 3 SDs from the mean. For all muscle groups, we used the Levene test to verify the assumption of equality of variances between groups. Descriptive statistics (mean and SD) of MIT (Nm) and normalized MIT (to body mass, Nm/kg) were calculated for all muscle groups and for all age groups for both boys and girls. These values represent the reference values per age group. The lower and upper bounds of the 95% CI of the mean of these values were also calculated. A multivariate analysis of variance (14 [age] × 2 [sex] × 10 repeated measures [muscle groups]) tested for significant differences between age groups and between boys and girls. When the multivariate Wilks λ of the interaction was significant, univariate post hoc tests with a Bonferroni correction were used to examine pairwise differences. The Pearson product-moment correlation coefficients were used to quantify bivariate relationships between torque and age, mass, and height. Stepwise multiple regression equations were used to determine the extent to which height, body mass, and age group predicted torque for the various muscles evaluated. All statistical analyses were performed using SPSS (SPSS 21.0 for Windows, Armonk, NY, USA), and significance was set at $\alpha < 0.05$ except for multiple comparisons where the alpha value was a more conservative $\alpha < 0.005$.

RESULTS

A total of 351 participants were recruited with 12 to 13 participants per sex per age group except for the 4-year-old group ($n = 11$). Torque data were normally distributed for all muscle groups except for knee extension and hip flexion. There were 2 outliers for knee extension (a 5-year-old boy and a 13-year-old girl) and 1 for hip flexion (a 17-year-old boy). These data were not included in the final analyses; thus, the results are based on 348 participants. The mean and SD for the MIT values for all muscle groups of both sexes according to each age group are reported in Table 1 (absolute values in Nm) and Table 2 (torque values normalized to body mass in Nm/kg) whereas the lower and upper bounds of the 95% CI of the mean of MIT values in Nm, and the mean of MIT values normalized to body mass in Nm/kg are reported in Table 3 and Table 4, respectively.

As shown in Table 1, a trend was seen for all muscle groups of boys to have higher torque values (Nm) than girls beginning with the 10-year-old group, as indicated by the light gray column. This difference is significant for the 15-, 16-, and 17-year-old age groups ($P < .0001$). The pattern was similar for the torque values normalized to body mass (Nm/kg), and some intersex differences did appear at younger ages than with the torque values. The male participants produced significantly greater ($P < .001$) torque in shoulder external rotation, elbow flexion and extension, hip flexion, extension, and abduction and in knee flexion beginning with the 14-year-old age group. Male participants 15 years and older were stronger than females in the same age groups for all muscle groups ($P < .0001$). Around the age of 12 to 13 years, a more abrupt change

TABLE 1

Mean of Maximal Isometric Torque Values in Nm (SD) for All Muscle Groups of Both Sexes (n = 13 Participants Per Sex Per Age Group) According to Each Age Group (n = 348)[a].

Muscle Group	Sex	Torque	Age (y)													
			4	5	6	7	8	9	10	11	12	13	14	15[c]	16[c]	17[c]
Shoulder abduction	F	Mean	5.1	8.3	9.3	11.3	15.0	16.7	20.7	20.0	31.7	39.0	46.8	47.1	46.1	49.9
		SD	1.4	3.0	3.0	4.9	4.2	9.1	6.6	4.1	9.0	16.0	5.0	9.4	9.6	9.5
	M	Mean	5.5	8.1	10.9	12.5	16.1	19.5	26.3	23.4	38.5	41.0	54.1	65.7	72.7	82.9
		SD	3.4	4.0	4.5	3.1	6.5	4.7	9.4	7.2	14.9	11.6	15.0	20.2	17.3	35.6
Shoulder external rotation	F	Mean	3.3	5.4	6.3	6.9	8.9	9.2	11.0	10.5	16.5	18.6	21.5	19.5	20.5	22.7
		SD	1.0	1.2	1.6	1.9	2.5	3.8	2.7	2.4	4.3	6.1	3.9	2.4	3.4	3.2
	M	Mean	4.2	5.7	7.4	7.7	10.4	11.3	14.2	14.5	18.3	19.2	25.6	29.5	32.9	33.0
		SD	1.8	2.0	1.8	1.7	3.5	2.4	4.6	2.9	5.1	4.6	4.6	6.6	7.7	8.4
Elbow flexion	F	Mean	4.6	8.0	9.6	11.0	15.7	15.8	19.4	20.0	29.9	33.4	37.8	38.6	38.8	40.6
		SD	1.3	1.9	2.7	2.8	3.3	6.3	4.8	3.6	6.3	6.7	5.0	4.8	6.3	8.4
	M	Mean	4.3	8.9	10.8	13.0	16.7	20.5	26.1	29.0	36.2	36.3	51.2	56.6	67.9	68.1
		SD	1.7	2.7	2.8	2.5	6.7	3.2	6.3	4.7	11.5	8.4	12.6	7.6	13.9	13.4
Elbow extension	F	Mean	5.2	8.5	8.6	8.8	11.5	12.1	15.3	14.6	21.3	24.5	24.6	25.1	26.2	28.3
		SD	1.4	3.0	2.9	2.6	3.0	5.1	4.4	3.5	5.3	5.1	4.1	4.9	3.0	4.7
	M	Mean	6.4	8.3	10.5	9.7	13.5	14.6	18.2	19.5	24.5	24.4	34.5	38.4	43.8	45.0
		SD	2.0	2.2	2.9	2.2	5.3	3.7	6.0	4.1	5.9	6.1	8.6	8.0	13.6	8.8
Hip flexion	F	Mean	15.1	16.7	18.7	21.5	30.4	32.3	38.6	41.1	53.3	59.4	76.9	83.4	85.4	87.9
		SD	2.7	6.1	3.2	4.7	6.9	11.3	4.0	7.1	12.1	13.3	16.6	13.3	11.4	19.9
	M	Mean	15.0	16.0	22.1	24.8	32.5	36.4	45.0	45.4	66.6	66.2	85.9	106.5	109.4	115.5
		SD	2.9	3.5	4.7	6.3	10.4	8.6	7.0	9.7	23.7	18.0	12.2	16.2	25.3	26.4
Hip extension	F	Mean	21.4	26.8	31.1	37.4	57.4	60.5	74.6	76.9	108.9	117.3	144.4	151.6	157.7	162.3
		SD	5.1	10.3	9.6	12.4	17.1	31.1	19.9	18.7	29.9	30.0	41.3	22.1	28.6	36.6
	M	Mean	20.7	26.7	32.7	39.8	61.1	74.9	91.9	92.8	131.7	137.5	185.6	206.4	245.4	257.6
		SD	9.4	12.0	12.7	10.5	28.6	21.7	20.1	25.2	41.4	36.8	29.2	40.9	49.5	54.3
Hip abduction	F	Mean	11.0	15.0	19.4	22.7	32.0	38.2	46.6	46.3	64.3	77.1	83.7	91.7	92.6	96.8
		SD	4.1	5.3	6.2	9.1	7.7	22.3	7.9	8.8	16.2	27.3	23.5	18.8	19.2	31.5
	M	Mean	9.2	15.2	22.5	26.2	32.2	43.2	56.5	58.5	79.1	79.7	106.8	127.7	139.1	151.4
		SD	4.8	6.4	8.2	5.4	10.6	9.8	12.1	9.0	26.1	21.9	35.1	26.3	27.0	38.0
Knee extension	F	Mean	16,9	22.9	30.6	33.2	50.3	55.0	56.5	73.7	91.6	97.4	128.3	129.2	132.7	144.3
		SD	3.3	3.7	6.3	12.2	13.5	17.4	15.4	20.6	22.7	25.9	38.9	23.2	27.3	32.0
	M	Mean	16.4	23.2	29.0	38.7	48.9	59.3	78.3	78.1	115.7	120.1	156.1	166.4	199.2	202.5
		SD	5.8	8.1	10.5	12.2	13.0	14.0	20.6	20.4	32.9	26.4	51.8	36.0	43.7	30.9
Knee flexion	F	Mean	9.3	14.7	19.0	22.2	30.5	32.9	39.2	45.4	58.6	61.1	80.7	82.0	86.5	88.5
		SD	1.7	3.3	3.2	5.6	6.3	9.6	7.3	11.1	12.9	8.1	12.3	10.2	12.2	18.3
	M	Mean	9.1	14.2	18.9	24.0	32.5	38.9	48.8	47.6	65.9	65.0	83.7	96.4	108.5	111.1
		SD	3.1	2.8	4.8	6.8	9.0	8.7	8.7	6.9	20.6	14.2	13.0	16.5	19.1	30.2
Ankle dorsiflexion	F	Mean	2.6	4.0	4.5	5.5	8.2	8.1	8.9	8.2	13.5	15.7	18.4	18.2	19.4	20.0
		SD	0.7	1.0	1.6	1.4	2.1	4.5	2.7	1.8	3.7	4.0	2.4	1.9	2.9	6.0
	M	Mean	1.9	3.8	4.5	5.0	6.8	8.6	11.6	12.2	15.9	15.9	20.5	24.7	27.9	26.3
		SD	0.7	1.4	1.6	1.3	2.5	2.5	3.1	7.1	5.3	3.5	5.0	5.2	5.7	5.3

[a]The light gray area shows the change in the trend for the boys to be stronger than girls, whereas the numbers within the dark gray show the more abrupt change in the strength progression in both girls and boys across age groups.

[b]Mean torque and standard deviation (SD) values are reported in Nm.

[c]Significant torque differences between girls and boys for all muscle groups in these age groups ($P < .0001$).

TABLE 2

Mean of Maximal Isometric Torque Values Normalized to Body Mass in Nm/kg (Standard Deviation [SD]) for All Muscle Groups of Both Sexes (n = 13 Participants Per Sex Per Age Group) According to Each Age Group (n = 348)[a]

Muscle Group	Sex	Torque[b]	Age (y)													
			4	5	6	7	8	9	10	11	12	13	14	15[c]	16[c]	17[c]
Shoulder abduction	F	Mean	0.33	0.41	0.39	0.49	0.50	0.53	0.60	0.64	0.66	0.71	0.82	0.84	0.80	0.89
		SD	0.12	0.14	0.16	0.21	0.12	0.17	0.21	0.11	0.15	0.13	0.14	0.13	0.14	0.12
	M	Mean	0.34	0.39	0.46	0.51	0.53	0.63	0.66	0.71	0.82	0.85	0.92	1.03	1.10	1.13
		SD	0.12	0.19	0.18	0.14	0.20	0.16	0.15	0.23	0.24	0.20	0.27	0.23	0.17	0.30
Shoulder external rotation	F	Mean	0.26	0.27	0.26	0.29	0.29	0.29	0.31	0.29	0.34	0.34	0.37[d]	0.35	0.36	0.34
		SD	0.10	0.06	0.09	0.07	0.06	0.05	0.08	0.09	0.06	0.04	0.06	0.04	0.07	0.04
	M	Mean	0.30	0.27	0.32	0.32	0.34	0.36	0.36	0.38	0.39	0.40	0.43	0.47	0.50	0.51
		SD	0.10	0.09	0.08	0.09	0.09	0.08	0.07	0.08	0.06	0.07	0.06	0.07	0.08	0.05
Elbow flexion	F	Mean	0.33	0.40	0.40	0.47	0.52	0.51	0.55	0.54	0.62	0.63	0.66[d]	0.69	0.68	0.68
		SD	0.10	0.09	0.14	0.12	0.10	0.11	0.13	0.11	0.10	0.13	0.12	0.07	0.11	0.08
	M	Mean	0.33	0.43	0.46	0.52	0.55	0.66	0.67	0.67	0.77	0.75	0.85	0.90	1.03	1.08
		SD	0.12	0.11	0.12	0.10	0.20	0.13	0.12	0.16	0.14	0.13	0.14	0.08	0.16	0.14
Elbow extension	F	Mean	0.38	0.38	0.36	0.37	0.38	0.39	0.44	0.40	0.44	0.46	0.48[d]	0.45	0.45	0.46
		SD	0.11	0.49	0.14	0.10	0.08	0.09	0.12	0.12	0.07	0.08	0.06	0.06	0.03	0.06
	M	Mean	0.40	0.40	0.41	0.40	0.44	0.47	0.46	0.47	0.53	0.53	0.57	0.61	0.66	0.68
		SD	0.10	0.12	0.12	0.12	0.14	0.14	0.12	0.14	0.06	0.09	0.10	0.10	0.17	0.10
Hip flexion	F	Mean	0.71	0.82	0.77	0.92	1.02	1.07	1.11	1.12	1.12	1.18	1.33[d]	1.37	1.37	1.47
		SD	0.18	0.26	0.18	0.19	0.20	0.26	0.17	0.21	0.26	0.39	0.18	0.29	0.18	0.27
	M	Mean	0.69	0.77	0.95	0.98	1.07	1.17	1.19	1.27	1.43	1.43	1.47	1.70	1.71	1.74
		SD	0.11	0.13	0.23	0.19	0.27	0.30	0.30	0.27	0.36	0.30	0.29	0.14	0.25	0.35
Hip extension	F	Mean	1.03	1.32	1.31	1.59	1.89	1.89	2.16	2.17	2.29	2.29	2.47[d]	2.91	2.75	2.81
		SD	0.27	0.47	0.56	0.50	0.38	0.36	0.65	0.46	0.66	0.82	0.47	0.35	0.42	0.52
	M	Mean	1.16	1.29	1.41	1.59	1.95	2.42	2.37	2.55	2.81	2.84	3.16	3.28	3.31	3.34
		SD	0.41	0.55	0.55	0.38	0.72	0.82	0.44	1.02	0.51	0.65	0.64	0.39	0.35	0.48
Hip abduction	F	Mean	0.58	0.74	0.81	0.97	1.06	1.19	1.34	1.34	1.33	1.43	1.44[d]	1.65	1.62	1.67
		SD	0.18	0.22	0.32	0.39	0.21	0.33	0.28	0.22	0.27	0.37	0.30	0.30	0.28	0.44
	M	Mean	0.54	0.73	0.96	1.05	1.06	1.41	1.46	1.49	1.68	1.65	1.78	2.03	2.10	2.15
		SD	0.18	0.27	0.35	0.19	0.36	0.41	0.23	0.40	0.31	0.34	0.45	0.26	0.24	0.46
Knee extension	F	Mean	0.98	1.13	1.27	1.41	1.68	1.84	1.82	2.01	2.11	2.14	2.14	2.19	2.20	2.21
		SD	0.30	0.13	0.35	0.48	0.37	0.53	0.44	0.61	0.47	0.48	0.50	0.46	0.37	0.41
	M	Mean	0.87	1.11	1.23	1.55	1.62	1.89	2.05	2.19	2.49	2.49	2.58	2.65	3.01	3.09
		SD	0.29	0.30	0.44	0.48	0.41	0.39	0.56	0.54	0.35	0.47	0.71	0.44	0.40	0.45
Knee flexion	F	Mean	0.57	0.73	0.79	0.95	1.02	1.09	1.13	1.23	1.22	1.18	1.21[d]	1.25	1.29	1.32
		SD	0.11	0.13	0.19	0.22	0.17	0.18	0.23	0.28	0.24	0.27	0.21	0.19	0.22	0.22
	M	Mean	0.56	0.69	0.81	0.95	1.07	1.25	1.27	1.35	1.41	1.35	1.41	1.55	1.64	1.65
		SD	0.16	0.12	0.21	0.20	0.24	0.27	0.22	0.22	0.29	0.24	0.21	0.24	0.11	0.20
Ankle dorsiflexion	F	Mean	0.19	0.20	0.18	0.24	0.27	0.25	0.26	0.26	0.28	0.30	0.31	0.32	0.33	0.35
		SD	0.06	0.05	0.08	0.06	0.06	0.07	0.09	0.05	0.08	0.07	0.07	0.04	0.06	0.09
	M	Mean	0.16	0.18	0.19	0.20	0.22	0.28	0.30	0.33	0.34	0.33	0.34	0.40	0.42	0.37
		SD	0.06	0.05	0.06	0.05	0.08	0.09	0.07	0.27	0.07	0.06	0.06	0.07	0.05	0.07

[a]The light gray area shows the change in trend for the boys to be stronger than girls, whereas the numbers within the dark gray show the more abrupt change in the strength progression in both girls and boys across age groups.
[b]Mean torque and standard deviation (SD) values are reported in Nm/kg.
[c]Significant torque differences between girls and boys for all muscle groups in these age groups ($P < .0001$).
[d]Significant torque differences between girls and boys for these specific muscle groups in these specific age groups ($P < .001$).

in the strength progression for all muscle groups was noted as observed from the torque values within the darker gray column (Table 1). But when using the torque values normalized to body mass (Nm/kg) as the reference values, the trend for the boys to be stronger than girls is shifted to the age of 9 years as indicated by the light gray column (Table 2), and the more abrupt change in the strength progression is shifted to around the ages of 11 to 12 years. This later observation, however, applies mainly to the stronger muscle groups such as the shoulder abductors, the elbow flexors, the hip extensors, and the knee extensors as indicated by the values within the darker gray areas (Table 2). The strongest muscle groups, for both absolute and torque values normalized to body mass, are by increasing order, the shoulder abductors, the elbow flexors, the elbow extensors, and the shoulder external rotators (upper limb) and the hip extensors, knee extensors, hip abductors, hip flexors, knee flexors, and ankle dorsiflexors (lower limb).

Strong, significant, positive correlations ($r = 0.81$ to 0.90; $P < .01$) were found between torque and body

TABLE 3

Lower and Upper Bounds of the 95% Confidence Interval (CI) of the Mean of Maximal Isometric Torque Values in Nm of All Muscle Groups of Both Sexes Across Age Groups (n = 348)[a]

		Age Group (Y)													
Muscle Group	**Sex**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Shoulder abduction	F	4.3	6.7	7.7	8.6	12.7	11.8	17.1	17.8	26.8	30.3	44.1	42.0	40.9	44.7
		5.9	9.9	10.9	14.0	17.3	21.6	24.3	22.2	36.6	47.7	49.5	52.2	51.3	55.1
	M	2.5	3.7	5	5.7	7.3	8.9	12.0	10.7	17.6	18.7	24.7	30	33.2	37.8
		8.5	12.5	16.8	19.3	24.9	30.1	40.6	36.1	59.4	63.3	83.5	101.4	112.2	128.0
Shoulder external rotation	F	2.8	4.7	5.4	5.9	7.5	7.1	9.5	9.2	14.2	15.3	19.4	18.2	18.7	21.0
		3.8	6.1	7.2	7.9	10.3	11.3	12.5	11.8	18.8	21.9	23.6	20.8	22.3	24.4
	M	3.2	4.6	6.4	6.8	8.5	10.0	11.7	12.9	15.5	16.7	23.1	25.9	28.7	28.4
		5.2	6.8	8.4	8.6	12.3	12.6	16.7	16.1	21.1	21.7	28.1	33.1	37.1	37.6
Elbow flexion	F	3.9	7.0	8.1	9.5	13.9	12.4	16.8	18.0	26.5	29.8	35.1	36.0	35.4	36.0
		5.3	9.0	11.1	12.5	17.5	19.2	22.0	22.0	33.3	37.0	40.5	41.2	42.2	45.2
	M	3.4	7.4	9.3	11.6	13.1	18.8	22.7	26.4	29.9	31.7	44.4	52.5	60.3	60.8
		5.2	10.4	12.3	14.4	20.3	22.2	29.5	31.6	42.5	40.9	58.0	60.7	75.5	75.4
Elbow extension	F	4.4	6.9	7.0	7.2	9.9	9.3	12.9	12.7	18.4	21.7	22.4	22.4	24.6	25.7
		6.0	10.1	10.2	10.2	13.1	14.9	17.7	16.5	24.2	27.3	26.8	27.8	27.8	30.9
	M	5.3	7.1	8.9	8.5	10.6	12.6	14.9	17.3	21.3	21.1	29.8	34.1	36.4	40.2
		7.5	9.5	12.1	10.9	16.4	16.6	21.5	21.7	27.7	27.7	39.2	42.7	51.2	49.8
Hip flexion	F	13.6	13.4	17.0	18.9	26.6	26.2	36.4	37.2	46.7	52.2	67.9	76.2	79.2	77.1
		16.6	20.0	20.4	24.1	34.2	38.4	40.8	45.0	59.9	66.6	85.9	90.6	91.6	98.7
	M	13.4	14.1	19.5	21.4	26.8	31.7	41.2	40.1	53.7	56.4	79.3	97.7	95.6	101.1
		16.6	17.9	24.7	28.2	38.2	41.1	48.8	50.7	79.5	76.0	92.5	115.3	123.2	129.9
Hip extension	F	18.6	21.2	25.9	30.7	48.1	43.6	63.8	66.7	92.6	101.0	121.9	139.6	142.2	146.4
		24.2	32.4	36.3	44.1	66.7	77.4	85.4	87.1	125.2	133.6	166.9	163.6	173.2	182.2
	M	15.6	20.2	25.8	34.1	45.6	63.1	81.0	79.1	109.2	117.5	169.7	184.2	218.5	228.1
		25.8	33.2	39.6	45.5	76.6	86.7	102.8	106.5	154.2	157.5	201.5	228.6	272.3	287.1
Hip abduction	F	8.8	12.1	16.0	17.8	27.8	26.1	42.3	41.5	55.5	62.3	70.9	81.5	82.2	79.7
		13.2	17.9	22.8	27.6	36.2	50.3	50.9	51.1	73.1	91.9	96.5	101.9	103.0	113.9
	M	6.6	11.7	18.0	23.3	26.4	37.9	49.9	53.6	64.9	67.8	87.7	113.4	124.4	130.7
		11.8	18.7	27.0	29.1	38.0	48.5	63.1	63.4	93.3	91.6	125.9	142.0	153.8	172.1
Knee extension	F	15.1	20.9	27.2	26.6	43.0	45.5	48.1	62.5	79.3	83.3	107.2	116.6	117.9	126.9
		18.7	24.9	34.0	39.8	57.6	64.5	64.9	84.9	103.9	111.5	149.4	141.8	147.5	161.7
	M	13.2	18.8	23.3	32.1	41.8	51.7	67.1	67.0	97.8	105.7	127.9	146.8	175.4	185.7
		19.6	27.6	34.7	45.3	56.0	66.9	89.5	89.2	133.6	134.5	184.3	186.0	223.0	219.3
Knee flexion	F	8.4	12.9	17.3	19.2	27.1	27.7	35.2	39.4	51.6	56.7	74.0	76.5	79.9	78.6
		10.2	16.5	20.7	25.2	33.9	38.1	43.2	51.4	65.6	65.5	87.4	87.5	93.1	98.4
	M	7.4	12.7	16.3	20.3	27.6	34.2	44.1	43.8	54.7	57.3	76.6	87.4	98.1	94.7
		10.8	15.7	21.5	27.7	37.4	43.6	53.5	51.4	77.1	72.7	90.8	105.4	118.9	127.5
Ankle dorsiflexion	F	2.2	3.5	3.6	4.7	7.1	5.7	7.4	7.2	11.5	13.5	17.1	17.2	17.8	16.7
		3.0	4.5	5.4	6.3	9.3	10.5	10.4	9.2	15.5	17.9	19.7	19.2	21.0	23.3
	M	1.5	3.0	3.6	4.3	5.4	7.2	9.9	8.3	13.0	14.0	17.8	21.9	24.8	23.4
		2.3	4.6	5.4	5.7	8.2	10.0	13.3	13.1	18.8	17.8	23.2	27.5	31.0	29.2

[a]Mean torque and standard deviations (SDs) are reported in Nm.

mass, height, and age for all muscle groups. For the upper limb muscle groups, stepwise multiple regression equations revealed that body mass accounted for the greatest percentage of the variance (83%-88%) in torque values. Adding age (mass + age [r^2 = 0.83-0.90]) and height (mass + age + height [r^2 = 0.86-0.90]) slightly improved the equations predictive value for all muscle groups. For the lower limb, for all muscle groups, a similar profile was found (r^2 = 0.76-0.81 for mass; 0.83-0.92 for mass + age). The addition of height (mass + age + height) did not improve the prediction of torque (r^2 = 0.83-0.89).

DISCUSSION

In this study, MIT reference values for Caucasian children and adolescents who were developing typically were established for 10 upper and lower limb muscle groups, using a standardized HHD protocol. Variations in torque between absolute and normalized to body mass values, and comparisons between the profiles of muscle strength progression between boys and girls, and between upper and lower limbs and across age groups were also reported. Finally, the extent to which body mass, age, and height predicted torque was determined. Very few outliers (n = 3, 0.85%) were found. There was no pattern for the

TABLE 4

Lower and Upper Bounds of the 95% Confidence Interval (CI) of the Mean of Maximal Isometric Torque Values Normalized to Body Mass in Nm/kg of All Muscle Groups of Both Sexes Across Age Groups (n = 348)

		Age Group (Y)													
Muscle Group	**Sex**	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Shoulder abduction	F	0.26-0.41	0.31-0.50	0.30-0.48	0.36-0.61	0.42-0.67	0.43-0.63	0.48-0.72	0.47-0.61	0.56-0.75	0.63-0.79	0.73-0.92	0.76-0.93	0.71-0.90	0.61-0.77
	M	0.26-0.42	0.26-0.52	0.34-0.58	0.42-0.59	0.40-0.65	0.53-0.72	0.57-0.76	0.57-0.85	0.66-0.97	0.73-0.97	0.75-1.09	0.75-1.09	1.00-1.20	0.94-1.32
Shoulder external rotation	F	0.20-0.32	0.23-0.31	0.21-0.31	0.25-0.34	0.26-0.33	0.26-0.33	0.27-0.36	0.24-0.34	0.30-0.38	0.32-0.37	0.33-0.41	0.33-0.38	0.31-0.40	0.32-0.37
	M	0.24-0.37	0.22-0.33	0.26-0.37	0.26-0.37	0.28-0.40	0.31-0.41	0.31-0.40	0.33-0.43	0.36-0.43	0.36-0.44	0.39-0.47	0.42-0.51	0.45-0.55	0.43-0.49
Elbow flexion	F	0.27-0.39	0.34-0.46	0.32-0.48	0.40-0.54	0.46-0.59	0.45-0.58	0.48-0.63	0.48-0.61	0.55-0.69	0.55-0.72	0.59-0.74	0.65-0.74	0.61-0.75	0.63-0.73
	M	0.26-0.41	0.35-0.50	0.38-0.54	0.46-0.58	0.42-0.67	0.58-0.74	0.60-0.74	0.57-0.76	0.68-0.86	0.67-0.83	0.77-0.94	0.86-0.95	0.94-1.13	0.84-1.01
Elbow extension	F	0.32-0.45	0.27-0.49	0.28-0.44	0.31-0.43	0.33-0.44	0.34-0.45	0.37-0.50	0.33-0.48	0.39-0.48	0.41-0.51	0.44-0.52	0.41-0.49	0.40-0.44	0.37-0.44
	M	0.34-0.46	0.33-0.48	0.37-0.53	0.33-0.47	0.35-0.53	0.38-0.56	0.38-0.54	0.39-0.55	0.49-0.57	0.45-0.56	0.51-0.64	0.55-0.67	0.56-0.77	0.51-0.65
Hip flexion	F	0.60-0.82	0.64-1.00	0.66-0.88	0.80-1.04	0.90-1.15	0.91-1.22	1.02-1.21	0.99-1.24	0.95-1.28	0.93-1.43	1.20-1.45	1.32-1.71	1.25-1.49	1.30-1.65
	M	0.62-0.76	0.68-0.86	0.79-1.10	0.87-1.09	0.90-1.24	0.98-1.36	1.00-1.39	1.11-1.44	1.20-1.65	1.19-1.56	1.28-1.65	1.61-1.78	1.51-1.81	1.42-1.86
Hip extension	F	0.87-1.19	1.01-1.63	0.99-1.63	1.29-1.89	1.64-2.13	1.68-2.11	1.78-2.53	1.69-2.25	1.87-2.71	1.77-2.81	2.16-2.79	2.68-3.14	2.47-3.03	2.32-2.97
	M	0.90-1.42	0.92-1.67	1.04-1.78	1.36-1.81	1.50-2.41	1.90-2.94	2.09-2.66	1.93-3.17	2.48-3.14	2.45-3.23	2.75-3.57	3.04-3.51	3.50-3.93	3.04-3.65
Hip abduction	F	0.47-0.69	0.59-0.89	0.62-0.99	0.73-1.21	0.93-1.19	0.99-1.39	1.18-1.50	1.01-1.27	1.16-1.50	1.19-1.66	1.24-1.64	1.45-1.85	1.34-1.71	1.39-1.95
	M	0.43-0.66	0.55-0.91	0.73-1.20	0.94-1.16	0.84-1.29	1.15-1.67	1.31-1.60	1.25-1.73	1.48-1.88	1.44-1.86	1.49-2.07	1.87-2.18	1.96-2.25	1.85-2.44
Knee extension	F	0.81-1.16	1.05-1.22	1.07-1.47	1.12-1.70	1.44-1.91	1.52-2.16	1.37-1.87	1.64-2.38	1.61-2.21	1.53-2.15	1.85-2.52	2.03-2.64	1.78-2.27	1.71-2.23
	M	0.68-1.06	0.91-1.31	0.93-1.53	1.27-1.82	1.36-1.89	1.64-2.14	1.70-2.41	1.77-2.41	2.26-2.71	2.00-2.58	2.13-3.03	2.39-2.92	2.77-3.26	2.61-3.16
Knee flexion	F	0.50-0.63	0.64-0.81	0.68-0.90	0.81-1.08	0.91-1.12	0.98-1.19	1.00-1.26	1.06-1.40	1.07-1.37	1.01-1.36	1.27-1.55	1.23-1.48	1.20-1.48	1.18-1.46
	M	0.46-0.66	0.60-0.77	0.67-0.96	0.83-1.06	0.91-1.22	1.07-1.42	1.13-1.41	1.21-1.48	1.23-1.60	1.20-1.50	1.28-1.55	1.40-1.69	1.58-1.71	1.42-1.67
Ankle dorsiflexion	F	0.15-0.22	0.17-0.23	0.14-0.23	0.20-0.27	0.24-0.31	0.21-0.30	0.21-0.31	0.19-0.25	0.23-0.33	0.25-0.34	0.28-0.37	0.28-0.34	0.28-0.36	0.29-0.40
	M	0.12-0.20	0.14-0.22	0.15-0.23	0.17-0.23	0.18-0.27	0.22-0.33	0.25-0.34	0.22-0.25	0.29-0.38	0.30-0.36	0.30-0.38	0.35-0.44	0.39-0.46	0.33-0.42

[a]Mean torque and standard deviations (SDs) are reported in Nm.

outliers. They varied in age, sex, and muscle group. The final analyses were done with 348 participants.

Strong correlations were found between torque and body mass, height, and age for all muscle groups in this present study. As reported by others with age groups similar to our own,[9,20] we found that body mass and age are the strongest predictors of strength when comparing across a wide age range. Although height has also been found to be a strong predictor of muscle strength in youth, this seems to apply to younger cohorts, that is, those of the age of 6 to 8 years.[23] A large sample of longitudinal data that tracks participants throughout childhood and adolescence is required to precisely determine the best predictors of muscle strength. As expected, no strength differences between sexes were observed for the younger age groups (those 14 years of age and younger). This finding is similar to previous work that showed that most strength differences between girls and boys occur after 12 to 13 years of age.[9,20] The more abrupt age-related change in the strength progression in both girls and boys that began at 11 to 13 years of age may be related to puberty, as also reported by others.[9,20] Changes in torque with age may reflect age-related improvements in coordination, more efficient neuromuscular activity, and muscle growth, processes which occur at different rates and to a differing extent in the various muscle groups.[30]

Eek et al[9] used a device similar to ours, and our results for torque values for the 5 to 15 years old are similar to theirs (within 1 SD of their values) except for the knee extensors of the 15-year-old adolescents and the ankle dorsiflexors for all age groups. For the knee extensors, the 15-year-old group in our study had higher values (>1 SD difference) than those in the Eek et al[9] study. This may be due to the use of a strap in our study, as this technique provides stabilization not present without its use. This means that higher isometric forces may have been able to develop (and be resisted by the examiner) using the present protocol compared with the protocol used by Eek et al. These differences may not have been present in the younger age groups due to their lower torque values. This suggests that the strap has an advantage in situations with higher torque values. For the ankle dorsiflexors, our values are consistently lower (>1 SD difference) than those of Eek et al. This suggests a methodological bias that can be attributed to differences in the lever arm measured and position of the HHD relative to the axis of the tibia. Because of the foot anatomy, if the surface of the dynamometer is placed perpendicular to a foot surface that is oblique relative to the axis of the tibia, the evaluator may record a force that is a combination of ankle dorsiflexor and evertor forces. In our study, the body of the HHD was always placed parallel to the axis of the leg centered on the second metatarsal. This ensured that the resulting force vector recorded by the device was always 1 at 90° relative to the surface of the foot and parallel to the longitudinal axis of the tibia. This technique allows recording a resulting force vector that is in the plane of dorsiflexion, meaning the force is more likely to be created only by the dorsiflexors.

Macfarlane et al[23] used a Microfet II HHD and reported isometric torque reference values for 6- to 8-year-old children. Our results for these age groups are similar to theirs where comparable muscle groups exist (hip abductors, knee flexors, and extensors), with 1 exception. The values reported by MacFarlane et al for the hip flexors are slightly higher than ours. This may be due to protocol differences. Macfarlane et al measured the hip flexors in sidelying with knees and hips flexed at 45°, which results in a lengthening of the hamstrings muscles compared with the position we used.

With regard to normalization of muscle strength, in youth, comparisons of muscle strength can be confounded by changes associated with growth such as body size or other growth-related parameters, which may hinder meaningful comparisons of strength measurements between groups, patients, or time points. The approach most commonly used for normalizing lower-extremity strength data in both children and adults is to divide force or torque measurements by the individual's body mass.[29,30] This is the approach that was used in this study, and torque values normalized to body mass in Nm/kg were reported per age group and sex. Unfortunately, no comparisons could be made with reference values in Nm/kg as to best of our knowledge, no such data were reported and this comment also applies for the 95% CI that were presented in this paper.

One of the main strengths of this study was the training of the evaluators and the calibration of the equipment prior to testing. The clinical utility of HHD measures, like any measure, is related at least in part to the quality of the information. One of the main threats to the validity and reliability of HHD is the capacity of the evaluator to resist the client's muscle force, especially when the muscle group being assessed is strong. In our clinical, teaching, and research experience with HHD, measurement errors from psychological (eg, motivation, attention, and concentration), biomechanical (eg, lever arm, angle of dynamometer, and plane of movement), and physiological (type of contraction, pain, motor unit recruitment, and length of agonist muscles) factors can be minimized with proper equipment, training, and practice. Optimal use of the reference values in this study also implies that the clinician is using well-maintained and calibrated equipment and that he or she has had sufficient training and practice to apply the protocol correctly and consistently. Best practice assumes that clinicians are adequately trained in the techniques that they use and that they maintain their skills. Introducing the use of HHD is no different than when a therapist is learning a new modality such as acupuncture, joint mobilizations, spinal manipulation, or soft tissue techniques. The proper use of any new modality of assessment or treatment requires new knowledge and additional skills that are acquired through structured training, practice, and adequate certification.

A second study strength is it provides reference values over a wide age range, for a large number of upper and lower muscle groups. Given that some children and adolescents use assistive devices to walk (and thus bear weight through their upper limbs) and given that some have bilateral upper and lower limb muscle weakness, reference values for both the upper and lower limbs are clinically useful. Thus, the reference data established in this study may help clinicians identify strength deficits in clients with conditions such as cerebral palsy, spina bifida, or various muscular dystrophies.

LIMITATIONS

A limitation of this study was the use of a somewhat small, convenience sample of youth that lived within a similar geographic location and were from a similar socioeconomic class. Thus, the reference values obtained may or may not be representative of the entire population of youth in the age groups assessed and therefore they cannot be considered normative values. Although the reference data presented in this study can be useful in clinical decision making, given the absence of normative data in the literature, a larger, more representative sample would obviously enhance the clinical utility of the data. Another limitation of this study is the approach used to normalize strength data, which was to divide the torque measurements by the individual's body mass. As noted above, longitudinal data would provide a better indication of the best methods for accounting for differences due to growth, maturation, and the interaction between these factors and sex. Finally, our study is also limited in that the intra- and interrater reliabilities of our protocol for children younger than 13 years and the concurrent validity of MIT with Cybex assessed by our HHD protocol for these youngest children are unknown. Further work is needed to establish this reliability and concurrent validity.

CONCLUSION

This study provides MIT reference values for several upper and lower limb muscle groups for children aged 4 years to 17 years who are developing typically. An HHD protocol that has previously been shown to be feasible, valid, and reliable was used to determine these values. These reference values may be helpful in the identification of strength impairments in several pediatric populations, especially when bilateral muscle strength impairment is present.

ACKNOWLEDGMENTS

The authors thank the children and parents who participated in this study. They also thank Thérèse Brousseau from the Neuro-Muscular Disease Program at the Quebec Rehabilitation Centre for her continued support of this work, and Élise Dubé, Sarah Dionne, and Ketsia Proulx, all physiotherapist students who have been significantly involved in the capture of the data (ED and SD), and the final formatting of the database and paper (KP). And they would also like to acknowledge their colleague Marc Perron, PT, MSc, who has significantly contributed to the revision of the manuscript, and Jean Leblond, our statistical consultant.

REFERENCES

1. Damiano DL, Martellotta TL, Sullivan DJ, Granata KP, Abel MF. Muscle force production and functional performance in spastic cerebral palsy: relationship of cocontraction. *Arch Phys Med Rehabil.* 2000;81:895-900.
2. Hill C, Croce R, Miller J, Cleland F. Muscle torque relationships between hand-held dynamometry and isokinetic measurements in children aged 9 to 11. *J Strength Cond Res.* 1996;10:77-82.
3. Lindeman E, Leffers P, Reulen J, Spaans F, Drukker J. Quadriceps strength and timed motor performances in myotonic dystrophy, Charcot-Marie-Tooth disease, and healthy subjects. *Clin Rehabil.* 1998;12:127-135.
4. Lohmann Siegel K, Hicks JE, Koziol DE, Gerber LH, Rider LG. Walking ability and its relationship to lower-extremity muscle strength in children with idiopathic inflammatory myopathies. *Arch Phys Med Rehabil.* 2004;85:767-771.
5. Merlini L, Bertini E, Minetti C, et al. Motor function-muscle strength relationship in spinal muscular atrophy. *Muscle Nerve.* 2004;29:548-552.
6. Styer-Acevedo J. Physical therapy for the child with cerebral palsy. In: Tecklin JS, ed. *Pediatric Physical Therapy*. 3rd ed. Philadelphia, PA: Lippincott Williams & Wilkins; 1999:107-162.
7. Wessel J, Kaup C, Fan J, et al. Isometric strength measurements in children with arthritis: reliability and relation to function. *Arthritis Care Res.* 1999;12:238-246.
8. 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;17:48-57.
9. Eek MN, Kroksmark AK, Beckung E. Isometric muscle torque in children 5 to 15 years of age: normative data. *Arch Phys Med Rehabil.* 2006;87:1091-1099.
10. Maltais DB, Wiart L, Fowler E, Verschuren O, Damiano DL. Health-Related physical fitness for children with cerebral palsy. *J Child Neurol.* 2014;29(8):1091-1100.
11. Hébert LJ, Remec JF, Saulnier J, Vial C, Puymirat J. The use of muscle strength assessed with handheld dynamometers as a non-invasive biological marker in myotonic dystrophy type 1 patients: a multicenter study. *BMC Musculoskelet Disord.* 2010;11:72.
12. Stuberg WA, Metcalf WK. Reliability of quantitative muscle testing in healthy children and in children with Duchenne muscular dystrophy using a hand-held dynamometer. *Phys Ther.* 1988;68:977-982.
13. Hébert LJ. *Évaluation De La Force Musculaire et Dynamomètres Manuels: concepts De Base et Applications Pratiques*. 3rd ed. Québec City, Canada: Bibliothèques et Archives nationales du Québec et Bibliothèque et Archives Canada; 2011.
14. 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.
15. Burns J, Redmond A, Ouvrier R, Crosbie J. Quantification of muscle strength and imbalance in neurogenic pes cavus, compared to health controls, using hand-held dynamometry. *Foot Ankle Int.* 2005;26:540-544.
16. Dawson C, Croce R, Quinn T, Vroman N. Reliability of the Nicholas manual muscle tester on upper body strength in children aged 8-10. *Pediatr Exerc Sci.* 1992;4:340-350.
17. Seagraves FE, Horvat M. Comparison of isometric test procedures to assess muscular strength in elementary school girls. *Pediatr Exerc Sci.* 1995;7:61-68.
18. Sullivan SJ, Chesley A, Hebert G, McFaull S, Scullion D. The validity and reliability of hand-held dynamometry in assessing isometric external rotator performance. *J Orthop Sports Phys Ther.* 1988;10:213-217.

19. Bäckman E, Oberg B. Isokinetic muscle torque in the dorsiflexors of the ankle in children 6-15 years of age. Normal values and evaluation of the method. *Scand J Rehabil Med.* 1989;21:97-103.
20. Beenakker EA, van der Hoeven JH, Fock JM, Maurits NM. Reference values of maximum isometric muscle force obtained in 270 children aged 4-16 years by hand-held dynamometry. *Neuromuscul Disord.* 2001;11:441-446.
21. Faigenbaum AD, Milliken LA, Westcott WL. Maximal strength testing in healthy children. *J Strength Cond Res.* 2003;17:162-166.
22. van den Beld WA, van der Sanden GA, Sengers RC, Verbeek AL, Gabreëls FJ. Validity and reproducibility of hand-held dynamometry in children aged 4-11 years. *J Rehabil Med.* 2006;38:57-64.
23. Macfarlane TS, Larson CA, Stiller C. Lower extremity muscle strength in 6- to 8-year-old children using hand-held dynamometry. *Pediatr Phys Ther.* 2008;20:128-136.
24. Harbo T, Brincks J, Andersen H. Maximal isokinetic and isometric muscle strength of major muscle groups related to age, body mass, height, and sex in 178 healthy subjects. *Eur J Appl Physiol.* 2012;112:267-275.
25. Bäckman E, Johansson V, Hager B, Sjöblom P, Henriksson KG. Isometric muscle strength and muscular endurance in normal persons aged between 17 and 70 years. *Scand J Rehabil Med.* 1995;27:109-117.
26. Saulnier J, Crête M, Hébert LJ, et al. *Protocole D'évaluation De La Force Musculaire à l'aide Du Dynamomètre Manuel Chez Les Enfants et les Adolescents*. Québec City, Canada: Institut de réadaptation en déficience physique de Québec; 2004.
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;23:289-299.
28. Bohannon RW. Literature reporting normative data for muscle strength measured by hand-held dynamometry: a systematic review. *Isokinet Exerc Sci.* 2011;19:143-147.
29. Wren TA, Engsberg JR. Normalizing lower-extremity strength data for children without disability using allometric scaling. *Arch Phys Med Rehabil.* 2007;88:1446-1451.
30. Jaric S. Muscle strength testing: use of normalisation for body size. *Sports Med.* 2002;32:615-631.
31. Hulley SB, Cummings SR, Browner WS, et al. *Designing Clinical Research: an Epidemiologic Approach*. 2nd ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2001.

APPENDIX

Standardized Positions for Each Muscle Group Tested With the Hand-Held Dynamometer (HHD)

Muscle Group[a]	Participant's Position	Limb/Joint Positions	HHD Placement
1. Shoulder abductors	Supine	Shoulder and elbow 0°, forearm in a neutral position	Most distal on lateral surface of arm, just proximal to lateral epicondyle of humerus
2. Shoulder external rotators	Supine	Shoulder 0°, elbow flexed 90°, forearm in a neutral position	Most distal on posterior surface of forearm, just proximal to wrist
3. Elbow flexors	Supine	Shoulder 0°, elbow 90° flexed, forearm in full supination	Most distal on flexor surface of forearm, just proximal to wrist
4. Elbow extensors	Supine	Shoulder 0°, elbow 90° flexed, forearm in full supination	Most distal on extensor surface of forearm, just proximal to wrist
5. Hip flexors	Supine	Hip and knee 90° flexed, leg supported on a stool on the table	Strap used and attached at one end in HHD hook attachment and at the other end around anterior surface of thigh, most distal, just proximal to knee fold
6. Hip extensors	Supine	Hip and knee 90° flexed, leg supported on a stool on the table	Strap used and attached at one end in HHD hook attachment and at the other end around posterior surface of thigh, most distal, just proximal to popliteal fold
7. Hip abductors	Supine	Hip and knee 0°, contralateral limb stabilized with a strap surrounding distal thigh and attached to the table	Most distal on lateral surface of thigh, on lateral epicondyle of knee
8. Knee flexors	Sitting	Knee 90° flexed, hip 90° flexed, trunk straight	Most distal on posterior surface of leg, just proximal to ankle
9. Knee extensors	Sitting	Knee 90° flexed, hip 90° flexed, trunk straight	On anterior surface of leg, just proximal to ankle, HHD surface inserted between the strap (surrounding the anterior surface of leg and leg of the table) and the subject's leg, 5 cm above lateral malleolus
10. Ankle dorsiflexors	Supine	Hip and knee 90° flexed, leg supported on a stool on the table, ankle 90° flexed, foot off table edge	Just proximal to metatarsophalangeal joints on dorsal surface of foot

[a]All muscle groups were tested with a Chatillon push-pull HHD (FCE-500, Ametek TCI Division, Chatillon Force Measurement Systems, Largo, Florida).