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Reliability of the three-dimensional pendulum test for able-bodied children and children diagnosed with cerebral palsy

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Abstract

This prospective study compared the test–retest reliability of thirteen variables calculated from the pendulum test in able-bodied children to those of children diagnosed with cerebral palsy. Ten healthy children and 10 children with a primary diagnosis of cerebral palsy (CP) (mean age 13 years) participated in the study. Data were collected using a three-dimensional motion analysis system on two separate occasions 73 ± 28 days apart. The between day reliability ICC scores of all variables were moderate to very high (0.60–0.98) for children with CP and high to very high (0.71–0.98) for able-bodied children. The children with CP demonstrated slower maximum angular velocity compared to the able-bodied children (202°/s versus 293°/s, $p < 0.01$). The time to maximum angular velocity occurred sooner for children with CP compared to able-bodied children (0.22 s versus 0.34 s, $p < 0.001$). For some children with CP, the knee motions demonstrated were not oscillations of decreasing magnitude. Therefore the integrals of knee motion in each plane were calculated. For both groups of subjects the largest integrals of motion were in the sagittal plane (knee flexion/extension). The able-bodied subject's integrals were twice as large compared to subjects diagnosed with CP ($p < 0.01$). High test–retest reliability of the variables suggests that the pendulum test provides an objective and reliable method to assess quadriceps spasticity in children with cerebral palsy.

Keywords: Cerebral palsy; Repeatability; Spasticity; Three-dimensional measurement; Pendulum

1. Introduction

Children with the primary diagnosis of cerebral palsy (CP) often present with gross motor limitations resulting in decreased ability to walk and transfer [1]. Increased tone/spasticity of the rectus femoris, hamstrings and gastrocsoleus muscle groups are often associated with causing impaired walking and transfer abilities for children diagnosed with CP [1–3]. Numerous potential interventions can be used to treat spasticity in children with CP. Determining the appropriate intervention and its effectiveness requires an objective, repeatable assessment of the spasticity impairment. Spasticity of the rectus femoris has been proposed as one potential cause for a stiff knee gait pattern (decreased knee flexion during swing) for children diagnosed with cerebral palsy [4]. This stiff knee gait pattern can result in a child tripping/falling when walking. Currently, a clinical test that is standardized, objective and repeatable to assess quadriceps spasticity is not routinely used.

The modified Ashworth scale [5] is often used clinically and in research as a way to assess spasticity, however it is only performed at a single speed [6]. It is an ordinal scale based on subjective evaluation of passive resistance perceived by the examiner and to date the reliability nor validity of the MAS has been reported in children with CP [3]. The MAS may not be sensitive enough to detect small changes in spasticity [6,7].

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In 1951 Dr. Robert Wartenberg, published "Pendulousness of the Legs as a Diagnostic Test" [8]. The pendulum test was performed on subjects sitting with both knees passively placed in full extension. The subject was instructed not to assist or to resist the swinging knee motions. The subject's legs were quickly pushed backwards and then allowed to swing freely. If no upper motor neuron involvement was present; the knee would demonstrate six or seven oscillations of flexion and extension; each oscillation demonstrating a smaller arc of motion. A sign of upper motor neuron involvement was reported to be a decrease in the length of time the knee would swing, or a decrease in the number of knee oscillations occurring during the test. A prolonged swinging of the knee would indicate a sign of lower motor neuron involvement. Wartenberg reported one limitation of the pendulum test involved getting the subjects to completely relax so not to affect the knee motions observed.

Since Wartenberg's publication, different versions of the pendulum test have been reported in the literature. The knee motions occurring during the pendulum test have been quantitatively measured using electrogoniometers [9], one-dimensional video analysis [10], magnetic tracking system [1], and three-dimensional motion analysis system [11]. The main focus of these three studies was to present the methodology of measuring the knee motions using each technology [9–11].

Two studies have reported on the repeatability of the pendulum test for able-bodied subjects [3,12]. In a test–retest (7–14 days apart) reliability of the pendulum test performed on able-bodied children 3–8 years old reported coefficient of variance ranging from 3 to 47% for variables calculated from the pendulum test [3]. An inter-day reliability study on able-bodied adults revealed a large range in reliability with ICC ranging from 0.08 to 0.88 on 10 variables recorded using an electrogoniometer [12]. To date, no studies hare reported the test–retest reliability of the pendulum test for subjects diagnosed with CP.

If spasticity is a velocity-dependent resistance to passive motion, then the maximum knee angular velocity during the pendulum test could be considered a measure of quadriceps spasticity. A number studies have assessed the changes in the pendulum variables after spasticity reducing interventions such as medications [5], anesthesia [1], and rhizotomy [3]. Six months after undergoing selective dorsal rhizotomy, the mean maximum knee angular velocity during the pendulum test were significantly increased postoperatively from preoperative values in subjects diagnosed with CP [3]. Nance et al. assessed the affects of tizanidine, a spasticity reducing medication that binds at the spinal and supraspinal levels, on quadriceps spasticity of 78 subjects with spinal cord injuries [13]. One of the reported results of the study was the subjects treated with tizanidine demonstrated reported more normal pendulum results [13].

If muscle tone is the muscle's resistance to passive stretch representing the mechanical-elastic characteristic of the muscle, then the different ratios calculated from the magnitude of the first swing of the pendulum test and the resting angle of the knee following the pendulum test could be considered measures of quadriceps tone. Three ratios are calculated from the pendulum test. These ratios are based on the amount of knee motion occurring during the first swing and the resting angle of the knee at the end of the pendulum test. Nordmark and Anderson report an increase in these ratios for subjects diagnosed with CP after undergoing rhizotomy [3]. Nance et al. reported an increase first swing excursion in subjects with spinal cord injuries treated with tizanidine, and no change for subjects treated with placebos [13]. Another study reported a similar response for patients diagnosed with multiple sclerosis treated with tizadine [10]. Fee and Miller compared the results of the pendulum test of eight able-bodied children and 10 children with a primary diagnosis of cerebral palsy awake and under anesthesia [1]. The phase plane plots of subjects with CP when awake were abnormal.

Under anesthesia, the phase plane plots of the subjects diagnosed with CP were almost identical to the able-bodied subject's phase plane plot [1]. However, because differences in the pendulum test were noted awake and under anesthesia for both groups, the author's concluded the pendulum test is a measure of an active component of spasticity (reflex), chronic changes in musculotendonous tissues, and the 'rest state' of muscle tone.

A reliability study examining the multiple variables calculated from the pendulum test is needed before the pendulum test can be used as a clinical measure of quadriceps spasticity to: determine the effectiveness of interventions, or discriminate different levels of spasticity of children diagnosed with CP. Therefore, the primary purpose of this study was to assess the test–retest reliability of thirteen kinematic variables calculated from the pendulum test in able-bodied children compared to those of children diagnosed with cerebral palsy over at least 1-month length of time. The second purpose of this study is to determine if the variables calculated are different between able-bodied children and children diagnosed with CP.

2. Materials and methods

2.1. Participants

All procedures were approved by our institutional review boards. After obtaining informed consent a convenience sample of 10 healthy children and 10 children with a primary diagnosis of cerebral palsy (CP) spastic diplegia participated in the study. The mean age of the able-bodied children was 14 years (±2.2) and 12 years (±2.4) of the children diagnosed with CP. The mean height was 160.7 cm (±13.7) for the able-bodied children and 143.4 cm (±16.4) for the children diagnosed with CP. Data were collected on two separate occasions; the average length of time between testing was 73 days (±28 days) for the able-bodied subjects and 72 days

(±27 days) for the subjects diagnosed with CP. The Gross Motor Function Classification System, (GMFCS) is a classification system for children diagnosed with CP based on self-initiated movements. Five of the children were a GMFCS level I, four of the children were a level II and one subject was classified as a GMFCS level III. For subjects diagnosed with CP the modified Ashworth scores [5] for quadriceps tone were 0 s for both legs of eight subjects. One subject demonstrated 1 MAS for one leg and 0 MAS for the other. The other subject demonstrated 2 MAS for one leg, and 0 MAS for the other leg.

2.2. Data processing and data analysis

Kinematic data were collected at 60 Hz for 15 s using a Motion Analysis Corporation Real Time System (EvaRT 4.4.4) with eight Eagle digital cameras. OrthoTrak 6.24 software was used to reduce and plot kinematic data (Motion Analysis Corporation, Santa Rosa, CA). The raw data were filtered using a Butterworth filter at 6 Hz. Electromyographic data was collected at 1000 Hz using Noraxon's TeleMyo 900 system (Noraxon USA Inc., Scottsdale, AZ) with surface silver–silver chloride electrodes (ConMed Corporation, Utica, NY). Study variables derived from the measured knee motions were calculated in Microsoft Excel. The average and standard deviation of the knee angle for the first 10 frames of data was defined as movement baseline. Movement onset and offset were defined as more than one standard deviation above this average knee angle. When calculated, the average movement onset/offset were 0.5° change in the knee angle in 1/60th of a second.

Because the subject lies supine to perform the pendulum test, the Cleveland clinic marker set was modified so the OrthoTrak software could be used to calculate the knee motions during the pendulum test. The "ASIS markers" were placed on the mid-point of iliac crest directly above the greater trochanter. The "PSIS marker" was placed over the umbilicus. The thigh marker triads were decreased in size to 8 cm in length and width to minimize interference of the mat with the triad, and were held in place with Co-flex®. The remaining markers were placed using the standard Cleveland Clinic protocol.

Surface electromyography of the vastus medialis oblique, rectus femoris and the semitendinosus were collected to confirmed that the muscles were not active prior to the test. To assist the subject in relaxing his/her muscles the electromyography system was connected to a speaker to provide audio feedback of the muscle activity. The trial was initiated when no audio feedback (representing quadriceps activity) were subjectively heard by examiner and subject.

Each subject was positioned lying comfortably on a bench (seat to floor height 30 in.) so the posterior calf did not contact the bench when the knee was in maximum flexion. This was performed to ensure that the mat did not impede maximum knee flexion. To allow for consistent positioning of each subject, the distance from the popliteal fossa to the edge of the mat was measured and used for both data collection days. If excessive hip rotation was noted during the practice trials, a small towel was placed under the distal third of the femur to decrease hip rotation. The examiner positioned the subject's leg in maximum knee extension. To control the starting position of the test, the distance from the heel of the foot to the floor was measured for the first trial, and the same distance was used for all trials on both data collection days. Prior to each trial, the subject was instructed to let the leg swing freely once it is released by the examiner. One to three practice trials were performed prior to data collection. Data collection with the motion analysis system was initiated approximately 1 s before the examiner released the subject's foot. After the subject's leg came to rest, at least 30 s passed before the next trial was performed. During data collection, the test was repeated if it appeared to the examiner the subject was assisting or resisting the knee motions. The procedures were repeated until three trials (without interference) of each leg were obtained for each subject. At least 4 weeks later the subjects returned for a repeat study. The order for data collection (right leg versus left) was randomized.

2.3. Data reduction

The variables calculated from the knee kinematic data during the pendulum test can be subdivided into three groups based on: the knee angular velocity, the knee oscillations, and the magnitude of knee motions in each plane. The following variables were calculated from the knee motions measured (Fig. 1).

2.3.1. Knee angular velocity variables

Maximum knee flexion angular velocity (°/s): The maximum knee flexion angular velocity occurring [3].

Time to maximum knee flexion angular velocity (s): The amount of time from initiation of movement to maximum knee angular velocity [11].

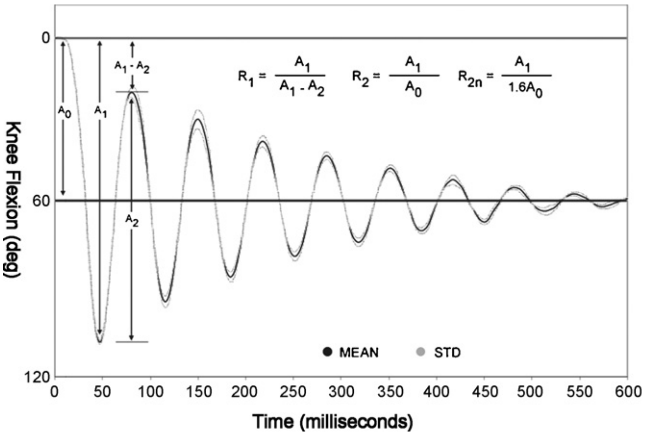

Fig. 1. An example of an able-bodied subject's knee motion during the pendulum test and ratio formulas calculated.

Table 1
Descriptive statistics of all variables calculated from the pendulum test for able-bodied participants ($n = 10$) and participants diagnosed with cerebral palsy ($n = 10$)

Variables (right leg)	Mean	Standard deviation	ICC	95% confidence interval for mean	
				Lower limit	Upper limit
Maximum knee flexion angular velocity (°/s) AB	292.51*	35.93	0.90	266.81	318.21
Maximum knee flexion angular velocity (°/s) CP	201.82	67.96	0.93	153.21	250.43
Time to maximum knee angular velocity (s) AB	0.34**	0.04	0.72	0.32	0.37
Time to maximum knee angular velocity (s) CP	0.23	0.07	0.60	0.18	0.27
Number of oscillations AB	6.9**	1.3	0.93	5.9	7.8
Number of oscillations CP	4.3	1.2	0.85	3.5	5.1
Duration of knee motion (s) AB	6.60**	1.59	0.97	5.47	7.74
Duration of knee motion (s) CP	2.60	1.22	0.94	1.73	3.48
Oscillation frequency (Hz) AB	1.05**	0.09	0.94	0.99	1.11
Oscillation frequency (Hz) CP	1.89	0.50	0.88	1.53	2.25
Sagittal plane integral (° s) AB	84.51**	23.65	0.95	67.59	101.43
Sagittal plane integral (° s) CP	25.08	15.34	0.94	14.11	36.06
Transverse plane integral (° s) AB	12.25*	7.69	0.79	6.75	17.74
Transverse plane integral (° s) CP	5.75	3.75	0.92	3.06	8.43
Frontal plane integral (° s) AB	24.95*	9.55	0.94	18.12	31.78
Frontal plane integral (° s) CP	8.39	9.54	0.98	1.56	15.21
A_0 [rest knee angle − start knee angle] (°) AB	61.14*	5.56	0.95	57.16	65.12
A_0 [rest knee angle − start knee angle] (°) CP	44.00	12.72	0.97	34.91	53.10
A_1 [max knee angle − start knee angle] (°) AB	105.14**	10.33	0.96	97.75	112.53
A_1 [max knee angle − start knee angle] (°) CP	49.78	25.58	0.96	31.49	68.08
R_1 [relaxation index] AB	4.16*	0.95	0.91	3.48	4.84
R_1 [relaxation index] CP	1.93	0.77	0.92	1.38	2.48
R_2 [A_1/A_0] AB	1.73*	0.14	0.92	1.62	1.83
R_2 [A_1/A_0] CP	1.08	0.31	0.92	0.86	1.30
R_2n [$A1/(1.6 \times A_0)$] AB	1.08*	0.09	0.93	1.02	1.14
R_2n [$A_1/(1.6 \times A_0)$] CP	0.68	0.19	0.92	0.54	0.81

AB: able-bodied subjects; CP: subjects diagnosed with CP.

* Significant difference ($p < 0.01$) between CP and able-bodied subjects.

** Significant difference ($p < 0.001$) between CP and able-bodied subjects.

2.3.2. Knee oscillations variables

Number of oscillations: The number of complete sine waves produced by the swinging leg [9].

Duration of oscillations (s): The duration of time from the onset of knee flexion until the cessation of knee movement [14].

Oscillation frequency (Hz): The number of oscillations (from one peak of knee flexion to the next peak of knee flexion) per second [11].

2.3.3. Magnitude of knee motion variables

A_0: The knee angle difference measured from the pre-release position to the final resting position [9].

A_1: The maximal knee angle difference measured during the first swing from the prerelease position [9].

A_2: The number of degrees difference between the first maximum knee flexion angle and the first minimum knee flexion angle [9]:

$$R_1 = A_1/(A_1 - A_2)$$

where R_2 (relaxation index) = A_1/A_0 [9] and R_2n (normalized relaxation index) = $A_1/1.6A_0$.

Previous study reported for able-bodied subjects, R_2 was 1.6 or more. Therefore by dividing the R_2 ratio by 1.6 would result in a quantification of spasticity, R_2n. A limb with spasticity would have a R_2n value of less than one, and a limb without quadriceps spasticity would have an R_2n value greater than one [9].

If the knee does not demonstrate oscillations, then the calculations from the previous described ratios (R_1, R_2, etc.) may not be meaningful, therefore the integrals were calculated. The integrals of sagittal, frontal, and rotational plane motions (° s) are defined as the area under the kinematic curve in each plane as a sum of degrees of knee motion by time component [11] (Tables 1 and 2).

SPSS software version 13.0 was used to perform statistical analysis. A one-way ANOVA based intra class correlation coefficients (ICC) with days 1 and 2 was calculated to assess the between days reliability of the pendulum test variables. Because only one examiner performed the test with each subject; a one-way mixed model ANOVA of absolute agreement was used. The ICC is an estimate of a measure's reliability, but it does not provide information regarding the precision of a measurement. Therefore, the 95% confidence interval of the mean was also calculated to provide an estimate of the precision of each variable reported [15]. The intra class correlation coefficient mixes random and systematic error, therefore the 95% limits

Table 2
Descriptive statistics of all variables calculated from the pendulum test for able-bodied participants ($n = 10$) and participants diagnosed with cerebral palsy ($n = 10$)

Variables (left leg)	Mean	Standard deviation	ICC	95% confidence interval for mean	
				Lower limit	Upper limit
Maximum knee flexion angular velocity (°/s) AB	294.63*	34.95	0.92	269.63	319.64
Maximum knee flexion angular velocity (°/s) CP	203.12	66.86	0.95	155.30	250.95
Time to maximum knee angular velocity (s) AB	0.34**	0.02	−0.062	0.33	0.35
Time to maximum knee angular velocity (s) CP	0.21	0.05	0.90	0.17	0.24
Number of oscillations AB	7.0*	1.6	0.97	5.8	8.1
Number of oscillations CP	4.7	1.2	0.84	3.8	5.6
Duration of knee motion (s) AB	6.79**	1.71	0.98	5.54	7.98
Duration of knee motion (s) CP	2.95	1.33	0.92	1.95	3.85
Oscillation frequency (Hz) AB	1.03**	0.06	0.71	0.99	1.08
Oscillation frequency (Hz) CP	1.75	0.38	0.87	1.47	2.02
Sagittal plane integral (° s) AB	87.09**	27.59	0.96	67.36	106.83
Sagittal plane integral (° s) CP	26.88	14.93	0.92	16.20	37.56
Transverse plane integral (° s) AB	11.40*	6.20	0.92	6.96	15.84
Transverse plane integral (° s) CP	5.50	3.00	0.85	3.36	7.65
Frontal plane integral (° s) AB	25.46*	10.54	0.88	17.93	33.00
Frontal plane integral (° s) CP	9.94	9.26	0.96	3.31	16.57
A_0 [rest knee angle − start knee angle] (°) AB	61.35*	5.55	0.97	57.38	65.32
A_0 [rest knee angle − start knee angle] (°) CP	46.53	13.60	0.97	36.80	56.26
A_1 [max knee angle − start knee angle] (°) AB	104.98**	11.49	0.97	96.76	113.20
A_1 [max knee angle − start knee angle] (°) CP	52.42	24.76	0.96	34.70	70.13
R_1 [relaxation index] AB	4.15*	0.94	0.89	3.47	4.83
R_1 [relaxation index] CP	1.78	0.61	0.88	1.34	2.21
R_2 [A_1/A_0] AB	1.71*	0.12	0.92	1.63	1.80
R_2 [A_1/A_0] CP	1.05	0.30	0.93	0.84	1.27
$R_{2}n$ [$A_1/(1.6 \times A_0)$] AB	1.07*	0.08	0.92	1.02	1.12
$R_{2}n$ [$A_1/(1.6 \times A_0)$] CP	0.68	0.16	0.93	0.56	0.79

AB: able-bodied subjects; CP: subjects diagnosed with CP.
* Significant difference ($p < 0.01$) between CP and able-bodied subjects.
** Significant difference ($p < 0.001$) between CP and able-bodied subjects.

of agreement was calculated for each variable (Tables 3 and 4). This is reported to be a measure of sampling error [16]. Because of the small sample size, nonparametric *t*-test (Wilcoxon, W) were used to compare the means of the variables between the two groups.

3. Results

Nonparametric *t*-test revealed no statistical difference between the right and left legs of the able-bodied children for all variables. However, the duration of oscillations and number of oscillations were statistically different between the right and left of the children diagnosed with CP ($p < 0.05$). Therefore, the results of each lower extremity are presented separately in Tables 1 and 2. For clarity, the results of the right lower extremity are described in this section.

3.1. Knee angular velocity variables

The maximum knee flexion angular velocity was significantly less in children with CP (202°/s) compared to able-bodied children (293°/s) ($p < 0.01$). The time to maximum knee flexion angular velocity was significantly less in children with CP (0.23 s) compared to able-bodied children (0.34 s) ($p < 0.01$). The time to maximum knee angular velocity for both groups of subjects (able-bodied and CP) demonstrated moderate ICC scores (0.60 for subjects with CP; ICC 0.72 for able-bodied subjects). (Tables 1 and 2).

3.2. Knee oscillations variables

On average, subjects diagnosed with CP demonstrated two fewer oscillations compared to the able-bodied subjects ($p < 0.01$). The number of knee oscillations demonstrated high to very high reliability (0.85 for subjects with CP; 0.93 for able-bodied subjects). The duration of time for knee oscillations was almost half as long for subjects diagnosed with CP (2.60 s) compared to the able-bodied subjects (6.60 s) ($p < 0.001$), with very high reliability (0.94 for subjects with CP; 0.97 for able-bodied subjects). The oscillations frequency was defined as the amount of time between each peak flexion oscillations. Subjects diagnosed with CP demonstrated larger oscillation frequency (1.89 Hz) compared to the able-bodied subjects (1.05 Hz) ($p < 0.001$). Oscillations frequencies demonstrated high and very high repeatability 0.88 for subjects with CP, and 0.94 for able-bodied subjects.

Table 3
Descriptive statistics and 95 % limits of agreement of all variables calculated from the pendulum test for able-bodied participants ($n = 10$) and participants diagnosed with cerebral palsy ($n = 10$)

Variables (right leg)	Mean difference	Standard deviation of mean difference	95% lower limits of agreement	95% upper limits of agreement	95% confidence interval for the lower limit of agreement		95% confidence interval for the upper limit of agreement	
Maximum knee flexion angular velocity (°/s) AB	−23.42	32.88	−87.86	41.01	−192.51	−112.09	65.24	145.66
Maximum knee flexion angular velocity (°/s) CP	−35.67	41.82	−117.63	46.29	−250.74	−148.44	77.10	179.39
Time to maximum knee angular velocity (s) AB	0.01	0.07	−0.13	0.14	−0.34	−0.18	0.19	0.35
Time to maximum knee angular velocity (s) CP	−0.01	0.12	−0.24	0.22	−0.62	−0.33	0.31	0.60
Number of oscillations AB	−0.77	0.57	−1.88	0.35	−3.69	−2.30	0.76	2.15
Number of oscillations CP	−0.13	1.30	−2.68	2.41	−6.81	-3.63	3.37	6.54
Duration of knee motion (s) AB	−0.75	0.62	−1.95	0.46	−3.92	−2.41	0.92	2.43
Duration of knee motion (s) CP	−0.43	0.85	−2.09	1.23	−4.79	−2.72	1.85	3.92
Oscillation frequency (Hz) AB	0.01	0.04	−0.07	0.09	−0.20	−0.10	0.12	0.22
Oscillation frequency (Hz) CP	0.13	0.49	−0.83	1.10	−2.41	−1.20	1.47	2.67
Sagittal plane integral (° s) AB	−10.54	14.80	−39.54	18.46	−86.64	−50.44	29.36	65.56
Sagittal plane integral (° s) CP	−6.18	9.77	−25.33	12.97	−56.43	−32.53	20.17	44.07
Transverse plane integral (° s) AB	−5.37	15.09	−34.95	24.20	−82.98	−46.07	35.32	72.23
Transverse plane integral (° s) CP	−0.60	2.76	−6.01	4.82	−14.80	−8.04	6.85	13.61
Frontal plane integral (° s) AB	−4.33	9.41	−22.77	14.11	−52.72	−29.70	21.04	44.06
Frontal plane integral (° s) CP	−0.96	2.55	−5.95	4.04	−14.06	−7.83	5.92	12.15
A_0 [rest knee angle − start knee angle] (°) AB	1.16	3.15	−5.01	7.32	−15.03	−7.33	9.64	17.34
A_0 [rest knee angle − start knee angle] (°) CP	−2.66	5.54	−13.52	8.20	−31.16	−17.61	12.28	25.83
A_1 [max knee angle − start knee angle] (°) AB	−2.87	5.34	−13.35	7.60	−30.36	−17.28	11.53	24.61
A_1 [max knee angle − start knee angle] (°) CP	−9.32	12.04	−32.92	14.28	−71.24	−41.79	23.15	52.60
R_1 [relaxation index] AB	−0.63	0.64	−1.89	0.63	−3.94	−2.36	1.10	2.68
R_1 [relaxation index] CP	−0.41	0.52	−1.43	0.61	−3.08	−1.81	1.00	2.27
R_2 [A_1/A_0] AB	−0.07	0.09	−0.24	0.10	−0.52	−0.30	0.16	0.37
R_2 [A_1/A_0] CP	−0.15	0.22	−0.57	0.27	−1.26	−0.73	0.43	0.96
R_2n [$A_1/(1.6 \times A_0)$] AB	−0.04	0.05	−0.15	0.06	−0.32	−0.19	0.10	0.23
R_2n [$A_1/(1.6 \times A_0)$] CP	−0.09	0.13	−0.36	0.17	−0.79	−0.46	0.27	0.60

AB: able-bodied subjects; CP: subjects diagnosed with CP.

3.3. Magnitude of knee motion variables

The remaining variables are calculated from the knee motions occurring during the pendulum test (Fig. 1). The majority of these variables (A_1, R_1, R_2 and R_2n) are based on the amount of knee flexion that occurs during the first oscillation of the pendulum test. For the children diagnosed with CP these variables were all significantly smaller compares to those of able-bodied children ($p < 0.001$). The between day ICC scores for these five variables were high to very high for the children diagnosed with CP (0.88–0.97) and for the able-bodied children (0.89–0.97). The variable A_0 (starting angle minus resting angle) was significantly less for children with CP compared to able-bodied children ($p < 0.01$).

For both groups (able-bodied and CP) the largest integrals (85° s for able-bodied subjects; 25° s for subjects diagnosed with CP) were in the sagittal plane (knee flexion/extension). The smallest integrals (12° s for able-bodied subjects; 6° s for subjects diagnosed with CP) were in the transverse plane (knee rotation). In the frontal plane, the able-bodied children demonstrated integrals significantly larger than the subjects diagnosed with CP (25° s versus 8° s; $p < 0.01$). The between day ICC scores for the integrals were high to very high ranged from for the children diagnosed with CP (0.85–0.98) and for the able-bodied children (0.79–0.96).

3.4. Modified Ashworth score

The modified Ashworth scale was not obtained for one of the 10 subjects on the second data collection session. For the nine subjects with diagnosed with CP, the modified Ashworth scale demonstrated high reliability for the right leg (ICC 0.778) and low reliability for the left leg (ICC 0.286).

4. Discussion

The purpose of this study was to examine the reliability of the pendulum test in able-bodied children and children diagnosed with CP. The data demonstrates high to very high between day test–retest reliability of the thirteen variables calculated from the pendulum test in able-bodied children and children diagnosed with cerebral palsy. The pendulum test has been shown to be a quantifiable measure of quadriceps spasticity, as evident by a more normal pendulum motion in subjects with upper motor neuron disorders after undergoing spasticity reducing interventions [1,3,5,13].

Table 4
Descriptive statistics and 95 % limits of agreement of all variables calculated from the pendulum test for able-bodied participants ($n = 10$) and participants diagnosed with cerebral palsy ($n = 10$)

Variables (left leg)	Mean difference	Standard deviation of mean difference	95% lower limits of agreement	95% upper limits of agreement	95% confidence interval for the lower limit of agreement		95% confidence interval for the upper limit of agreement	
Maximum knee flexion angular velocity (°/s) AB	−9.53	28.80	−65.99	46.92	−157.67	−87.21	68.14	138.61
Maximum knee flexion angular velocity (°/s) CP	−25.78	50.06	−123.89	72.33	−283.23	−160.78	109.21	231.66
Time to maximum knee angular velocity (s) AB	−0.02	0.05	−0.12	0.08	−0.28	−0.16	0.12	0.25
Time to maximum knee angular velocity (s) CP	−0.02	0.06	−0.14	0.09	−0.32	−0.18	0.13	0.27
Number of oscillations AB	−0.37	0.46	−1.26	0.53	−2.72	−1.60	0.87	1.98
Number of oscillations CP	−0.57	1.31	−3.13	1.99	−7.28	−4.09	2.95	6.15
Duration of knee motion (s) AB	−0.49	0.53	−1.53	0.56	−3.23	−1.93	0.95	2.25
Duration of knee motion (s) CP	−0.77	1.18	−3.08	1.54	−6.83	−3.95	2.41	5.29
Oscillation frequency (Hz) AB	0.01	0.08	−0.15	0.16	−0.41	−0.21	0.22	0.42
Oscillation frequency (Hz) CP	0.18	0.31	−0.44	0.79	−1.44	−0.67	1.02	1.79
Sagittal plane integral (° s) AB	−12.81	19.33	−50.69	25.08	−112.22	−64.94	39.32	86.60
Sagittal plane integral (° s) CP	−8.78	12.98	−34.22	16.67	−75.54	−43.78	26.23	57.99
Transverse plane integral (° s) AB	−2.01	7.35	−16.42	12.40	−39.82	−21.83	17.82	35.80
Transverse plane integral (° s) CP	−2.01	3.65	−9.18	5.15	−20.81	−11.87	7.84	16.78
Frontal plane integral (° s) AB	−9.04	11.95	−32.46	14.39	−70.51	−41.27	23.20	52.43
Frontal plane integral (° s) CP	−2.53	5.48	−13.26	8.21	−30.69	−17.29	12.24	25.64
A_0 [rest knee angle − start knee angle] (°) AB	0.00	2.99	−5.85	5.86	−15.36	−8.05	8.06	15.37
A_0 [rest knee angle − start knee angle] (°) CP	−4.23	6.79	−17.54	9.08	−39.16	−22.54	14.08	30.70
A_1 [max knee angle − start knee angle] (°) AB	−1.40	5.41	−12.01	9.21	−29.24	−16.00	13.20	26.45
A_1 [max knee angle − start knee angle] (°) CP	−9.49	19.42	−47.56	28.58	−109.40	−61.88	42.90	90.42
R_1 [relaxation index] AB	−0.62	0.97	−2.52	1.28	−5.60	−3.23	1.99	4.36
R_1 [relaxation index] CP	−0.46	0.59	−1.62	0.71	−3.51	−2.06	1.15	2.60
R_2 [A_1/A_0] AB	−0.02	0.09	−0.20	0.15	−0.48	−0.27	0.22	0.43
R_2 [A_1/A_0] CP	−0.07	0.29	−0.63	0.49	−1.55	−0.85	0.70	1.41
R_2n [$A_1/(1.6 \times A_0)$] AB	−-0.02	0.06	−0.12	0.09	−0.30	−0.16	0.13	0.27
R_2n [$A_1/(1.6 \times A_0)$] CP	−0.04	0.16	−0.34	0.26	−0.84	−0.46	0.38	0.76

AB: able-bodied subjects; CP: subjects diagnosed with CP.

Only one previously published study has reported the inter day repeatability of the pendulum test over time in subjects with a upper motor neuron impairment (following a cerebral vascular) [17]. The intra-subject variability (using the coefficient of variance) was reported to range from 1 to 31.5% for the R_2n variable (A_1/1.6A$_0$). In regards to the variability between sequential testing sessions the authors reported: "we failed to demonstrate significant variations between values obtained" (p. 343–344) [17].

Unfortunately no other statistical correlations or analysis were provided. In comparison, for our subjects diagnosed with CP, the between day coefficient of variance for the R_2n ratio ranged was 24% for the right leg and 28% for the left leg. For the able-bodied subjects the coefficient of variance was 7% for the left leg and 8% for the right.

Because of the small sample size and small variance, the time to maximum angular velocity was the only variable not to demonstrate high repeatability. For the right leg the ICC was 0.60 for children with CP and 0.72 for able-bodied children. For the left leg the time to maximum angular velocity demonstrated an ICC of.90 for children with CP. The interclass correlation coefficient is a ratio of the variance of a measurement over the sum of the variance and error of the measurement; because the variance was 0.000 for the able-bodied subjects the ICC could not be calculated, resulting in the ICC reported of −0.062. However, a nonparametric t-test for the time to maximum angular velocity was not statistically significantly different between the right and left leg for both groups of subjects ($p > 0.05$). The increased variability for the children diagnosed with CP may be due variability within the subjects. Considering the time to maximum angular velocity was 0.34 s for able-bodied children and 0.23 s for children diagnosed with CP; a larger sample size may better assess the repeatability of this variable calculated from the pendulum test.

Able-bodied subjects demonstrate a decreasing magnitude of knee motion with each oscillation. For the children with CP, some of the children demonstrated knee oscillations of decreasing magnitude (Fig. 2) and others did not

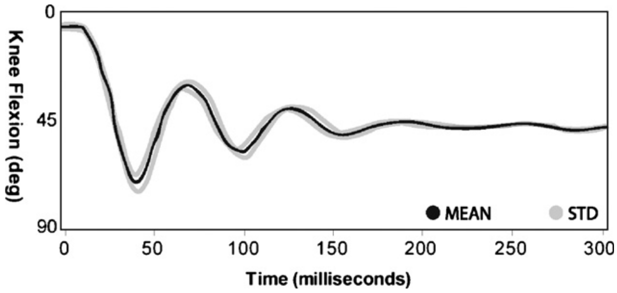

Fig. 2. An example of oscillating knee motion during the pendulum test of a child diagnosed with CP.

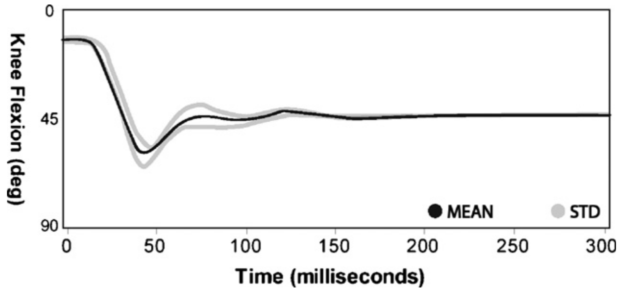

Fig. 3. An example of non-oscillating knee motion during the pendulum test of a child diagnosed with CP.

demonstrate knee oscillations (Fig. 3). Previous authors have suggested that an integral of the sagittal plane knee motions may be a more sensitive measure of knee motions [9]. The sagittal plane integral of knee motion is not dependent on the knee demonstrating oscillations of decreasing magnitude. The sagittal plane integral for children diagnosed with CP was one third as large as the sagittal integral for the able-bodied children. For both groups, the sagittal plane integral demonstrated high repeatability. Therefore the sagittal plane integral may be a better variable to measure knee motion than previously reported ratios (R_1, R_2n, and R_2) which are dependent on multiple oscillations.

Previous literature reported that motions other than knee flexion/extension may be an indicator of spasticity, however these studies used visual or two-dimensional assessments of knee motion [8,9,12,14]. By using a three dimensional motion analysis system, the knee motions in all three planes (sagittal, frontal and transverse) were measured. For all subjects, the sagittal plane integrals were three and seven times greater than the frontal and transverse plane integrals, respectively. Because of the relatively small magnitude of frontal and transverse plane motions, three-dimensional motion analysis may not be required to perform the pendulum test, and using an electrogoniometer may be an acceptable alternative.

The clinician performing data collection in this study has 11 years experience using the modified Ashworth scale and 10 years experience applying the motion analysis system markers. The large variability in repeatability of the modified Ashworth scale (ICC 0.778 right leg and ICC 0.286 left leg) is a limitation of the Ashworth scale which has been previously alluded to by Nordmark and Andersson [3]. For the 10 children diagnosed with CP, 17 of the 20 limbs on the first visit of and 14 of the 18 limbs on the second visit were graded a zero, no increase in tone, using the modified Ashworth scale. The relatively high reliability of the pendulum test illustrates the sensitivity differences in these two measures. The results of this study suggest that the pendulum test provides an objective and reproducible measure of quadriceps spasticity in children diagnosed with CP; however future studies to assess if the pendulum test can discriminate different levels of spasticity are needed.

One limitation of the pendulum test is that the amount of influence due to muscle spasticity, tone and/or changes in musculotendonous tissues cannot be differentiated clinically. Because of the large number of variables that have been calculated from the pendulum test future studies to decrease the number of variables calculated from the pendulum test would be beneficial. We propose the maximum angular knee velocity and the time to maximum angular knee velocity variables could be used as measures of the active component of quadriceps spasticity. The A_0 variable (resting knee angle – start knee angle) could be used as a measure to assess the resting state of quadriceps tone and quadriceps tightness due to the chronic changes in the quadriceps musculotendonous tissues. The sagittal integral calculated could be used as a measure of overall quadriceps interfere due to spasticity, tone and tightness of the quadriceps.

From the findings of this study we believe implementing the pendulum test (using motion analysis or an electrogoniometer) to better objectively quantify quadriceps spasticity in clinical care and future research assessing quadriceps spasticity is warranted.

Future studies to assess the relationship between quadriceps spasticity (measured with the pendulum test) to functional measures of mobility (GMFM, walking velocity, and knee kinematic data) are also needed.

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