Normative Data and Predictors of Leg Muscle Function and Postural Control in Children

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ABSTRACT

HAZELL, T. J., A. K. SHARMA, C. A. VANSTONE, I. GAGNON, T. T. PHAM, S. L. FINCH, H. A. WEILER, and C. J. RODD. Normative Data and Predictors of Leg Muscle Function and Postural Control in Children. *Med. Sci. Sports Exerc.*, Vol. 46, No. 11, pp. 2184–2190, 2014. **Introduction**: At the present there are limited tools available to measure muscle function in young children. Ground reaction force plates measure lower-body function and postural control in older children and adults. The purpose of this study was threefold: 1) develop normative data for evaluating global muscle development; 2) determine the reproducibility of ground reaction force plates for assessing muscle function in preschool-age children; and 3) identify predictors of skeletal muscle function. **Methods**: Children's (n = 81, 1.8 to 6.0 yr; M = 52%) muscle function and postural control was measured for jump (JMP), sit-to-stand (STS), and both undistracted and distracted body sway tests using a ground reaction force plate (Kistler 9200A). Whole body composition used dual-energy x-ray absorptiometry (Hologic 4500A Discovery Series). Plasma 25-hydroxyvitamin D [25(OH)D] and parathyroid hormone concentrations were measured by chemiluminescence (Liaison, Diasorin, Mississauga, ON, Canada) as well as ionized calcium (ABL80 FLEX, Radiometer Medical A/S). Demographics, and anthropometry were collected. ANOVA and linear regression were used to identify predictors. Reproducibility was assessed by intersubject coefficient of variation. **Results**: Age was a consistent predictor in all models; body size or fat and lean mass were important predictors in 3 of the models – STS peak force, STS peak power, and JMP peak power. STS was the most reproducible maneuver (average coefficient of variation =15.7%). Distracted body sway testing was not appropriate in these youngsters. **Conclusion**: The novel data presented in this study demonstrate a clear age (developmental) effect without any effect of sex on muscle function and postural control in young children. Lean muscle mass was important in some models (STS peak force and JMP peak power). The STS test was the best of the 4 maneuvers. **Key Words:** JUMPING MECHANOGRAPHY, SIT-TO-STAND, CENTER OF PRESSURE, GROUND REACTION FORCE, MUSCLE POWER, PEDIATRIC

Although there are some limited tools for evaluating a child's muscular strength, such as grip strength (19), more comprehensive methods measuring other regions of the body (trunk and legs) would allow for more extensive evaluation of the muscle and musculoskeletal relations in developing children (14,33). Portable ground reaction force plates have recently been evaluated as a potential tool for assessing muscle function in children and adolescents, with reproducible outcomes and a consistent relation with body size (14,33,39). Muscle function can be defined as the coordinated contraction of individual muscle fibers within each skeletal muscle generating muscle force or power (14,17,33). One such maneuver is a standing countermovement jump (JMP) on the platform, with strength and power derived from ground reaction force data (23). "Jumping mechanography" has been validated in school-age children and adolescents (14,33,39) whereas other force plate assessments of muscle function during other tasks, such as sit-to-stand (STS) or body sway (BS), have been used across toddlers, adolescents, adults, and older adults with reproducible results (3,7,14,28,33,39). Although all represent developmentally appropriate tasks that can be easily elicited in this age group, none of these maneuvers (JMP, STS, or BS) have been extensively evaluated in healthy preschoolers. In this study, we demonstrate that these tools can also be used to evaluate changes in strength, power, and neuromuscular maturation during this period of rapid development of skeletal muscle, coordination, and postural control (13).

Because young children undergo such rapid growth, changes in body composition, and postural control, these

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factors are likely important predictors of muscle function. Recently, we reviewed the importance of vitamin D status in skeletal muscle function (17); several studies in both children and older adults have demonstrated vitamin D insufficiency associated with reduced muscle strength and concomitant reductions in muscle mass (9,12,26,31,38,40,41). There is also evidence to support the important role of vitamin D in muscle strength/function (2,4). Similarly ionized calcium concentrations are associated with increased muscle contractility, whereas parathyroid hormone (PTH) has been negatively associated with muscle mass (18). As a result, these minerals and calcitropic hormones are potential determinants of skeletal muscle function in young children.

Therefore, this study seeks 1) to initiate the development of normative data for evaluating leg muscle function and postural control, and 2) to identify physiological predictors of skeletal muscle function (i.e., vitamin D status, lean mass, body mass index (BMI) *z*-score, and sex).

METHODS

Participants

Children (1.8 to 6 yr) were studied between June 2010 and June 2011 from a random sample of licensed daycares (n = 77) in the Montréal area (45°N, 73°W). Detailed methods have been published (8). A subset (n = 81) of children (42 boys and 39 girls, 4.0 ± 1.0 yr; Table 1) visited our research facility, where their height and body mass were measured using a stadiometer (Detecto, Webb City, MO). Height-for-age and body mass-for-age *z*-scores (BAZ) were calculated using the World Health Organization 2007 reference data (World Health Organization Anthro and AnthroPlus, Geneva, SUI). Parents provided written informed consent, and this study was approved by the McGill University Faculty of Medicine Institutional Review Board. Although the main part of the parent study involved data collection (blood sample) at daycare centers, the anthropometry, body composition, and muscle function data were collected at the Mary Emily Clinical Nutrition Research Unit of McGill University.

Body Composition

Whole body composition (lean and fat mass) was measured using a fan-beam dual-energy x-ray absorptiometry (DXA) device (APEX version 13.2:3, Hologic 4500A Discovery Series, Bedford, MA). Children wore standardized clothing (shorts and T-shirt). The DXA spine phantom with known density (1.024 $g\cdot cm^{-2}$) yielded a bone mineral density coefficient of variation (CV) of 0.3% (244 scans).

Biochemistry

A nonfasted 1.1-mL capillary blood sample (heparinized) was collected at 0800 to 1200 h via a finger lancet at daycare. Samples were stored on ice for transportation to the laboratory and centrifuged at 3000*g* under 4°C for 20 min to derive the plasma, which was then stored at −80°C until analysis. Plasma total 25(OH)D and bioactive 1–84 PTH concentration were measured using a chemiluminescence assay (Liaison, Diasorin, Mississauga, ON, Canada). The interassay and intraassay CV for high and low assay controls were <8% for 25(OH)D and ≤15% for PTH. Ionized calcium was measured in 0.1 ml whole blood (ABL80 FLEX Radiometer Medical A/S, Copenhagen, Denmark). The normal reference range for PTH is 1.06 to 5.83 $pmol\cdot L^{-1}$ (5), and iCa is 1.12 to 1.32 $mmol\cdot L^{-1}$ for this age group (24).

Muscle Function Measurements

All children performed three maneuvers on a ground reaction force plate (Type 9200A; Kistler Instrument Corp., Novi, MI): jumping (14), sit-to-stand (23), and an undistracted BS analysis (21,32). The Kistler device measures forces applied to the plate (ground reaction forces) over time, allowing a mathematical derivation of measures of strength, power, and sway. The device was calibrated daily. All children received instruction, proper demonstration, as well as practice attempts before completing any muscle function test.

Jumping test. Children performed a standard countermovement jump, which started in the standing position while centered on the force platform with the feet hip width apart and hands at sides (14,33,39). The two-legged jump was initiated by bending the knees then jumping vertically, as high as possible, and landing back on the force plate. Participants were instructed to place their hands at their sides and not to use them to push off or swing their arms, and then bend their knees and jump as high as they could. This jump effort was repeated five times with approximately 2 s between efforts.

Sit-to-stand test. Children started in a seated position with feet resting flat on the force platform, hands crossed over their thorax, and knees at 90° flexion (27); the chair height was adjusted accordingly. The sit-to-stand movement was initiated by rising out of the chair without any upper body help, pausing for 5 s once standing and then sitting

TABLE 1. Subject characteristics.

Group	*n*	Sex (*n*)	Age (yr)	Height for Age *z*-Score	Body Mass for Age *z*-Score	BMI for Age *z*-Score	Lean Mass (kg)	Fat Mass (kg)
<3 yr	15	M (7), F (8)	2.5 ± 0.4	−0.3 ± 0.9	0.0 ± 0.9	0.3 ± 1.1	9.2 ± 1.0	4.3 ± 1.1
3–3.9 yr	21	M (12), F (9)	3.4 ± 0.3	−0.4 ± 1.2	0.4 ± 1.1	1.0 ± 0.9	10.7 ± 1.5	5.1 ± 0.9
4–4.9 yr	28	M (13), F (15)	4.5 ± 0.3	−0.2 ± 0.7	0.0 ± 0.7	0.2 ± 0.7	12.7 ± 1.6	4.6 ± 1.3
≥5 yr	17	M (10), F (7)	5.3 ± 0.3	0.1 ± 1.1	0.2 ± 0.9	0.3 ± 0.8	14.2 ± 2.1	4.9 ± 1.1

M, male; F, female.

back in the chair. Children were instructed to sit on the chair, put their hands on their stomach, keep the feet flat on the force plate, then stand up out of the chair, pause at the top, and sit back down. This sit-to-stand effort was repeated five times with approximately 5 s between efforts.

BS test. This test was completed in two parts. The first had the child start in a standing position on the force platform with the feet hip width apart and hands at sides. The BS effort had the participants stand as still as possible for 30 s. In order to increase BS, we first attempted to have the children stand with their eyes closed; almost all children piloting this study refused to do so. The second part was replaced with a distracted BS test; the child repeated the initial BS test but answered questions to distract from this task. The force platform measured changes in the center of pressure. Although it would have been more comparable with adult methods to measure BS with eyes closed and with distraction, this was not feasible in the young participants.

Analysis

All force plate data acquisition used the manufacturers' Bioware® Software Type 2812A Version 4.0× (Kistler Instrument Corp.) and was analyzed using customized software in R (36). All data were analyzed by the same investigator (T. J. H.) who inspected and chose the best individual JMP and STS efforts. As each jump data file contained multiple maneuvers, the single largest jump was selected for analysis (14,33,39). Each individual jump had a beginning (subject was standing still on platform) and end (subject had jumped and was no longer on the platform, i.e., lift-off). For each jump, software extracted the peak force and peak force relative to body mass. Numerical integration of the force (acceleration) versus time curve yielded center-of-mass velocity, peak power, and relative peak power (power = force × velocity). The integration began at the start of the maneuver. Similarly, the single largest effort was selected for analysis from multiple sit-to-stand maneuvers. Each sit-to-stand maneuver had a beginning (subject sitting still) and an end (subject standing motionless). The customized software then extracted the peak force and calculated the slope of the force versus time curve from 20% to 90% of peak force, which is a surrogate for peak power based on studies of isokinetic muscle power in the Nottingham power rig (23). The single best effort was used in analysis for the JMP and STS assessments; this was done in an effort to be consistent with previous pediatric literature on muscle function using force plates (14,33,39) and theoretical studies suggesting this is a more reproducible measure when intraindividual variability is high (1). For each BS assessment, the beginning of the test was selected and the first 5 s discarded to allow for stabilization. BS amplitude and sway velocity were calculated from the following 15 s (21,32).

Reproducibility. The repeatability (intraobserver) of each test was performed on nine children representing 11% of our subjects. The short-term error (E_{ST}) was calculated for JMP peak force, peak power, STS peak force, proxy power, and BS amplitude and sway velocity using the formula [$100(\mathrm{Absolute}(x_1 - x_2))/((x_1 + x_2)/2)$], where x_1 is the value from the original test and x_2 is the value from the repeat test (29). The learning error (E_{LE}) was also calculated for the same measures as E_{ST} using the formula [$100((x_2 - x_1)/x_1)$] (29). For the same measures, the intersubject CV was also determined within each annual age category using the equation [100(SD/mean)] (29,39).

Statistical Analysis

Reproducible jump measures include JMP peak power, STS peak force, STS peak power, and BS amplitude

TABLE 2. Muscle strength/power and postural control output for sit-to-stand, jump, and BS.

		n		Peak Force (N)		Relative Peak Force (N·kg^{-1})		Peak Power (N·s^{-1})[a]		Relative Peak Power (N·s^{-1}·kg^{-1})	
	Age	M	F	M	F	M	F	M	F	M	F
STS	<3	7	7	149.5 ± 24.1	151.9 ± 15.8	11.1 ± 0.9	11.7 ± 0.9	723.8 ± 264.0	900.7 ± 529.1	53.4 ± 18.5	70.4 ± 42.3
	3–3.9	12	9	182.7 ± 28.2	194.7 ± 39.1	11.8 ± 1.3	10.8 ± 1.2	1169.0 ± 480.2	1190.8 ± 464.9	76.4 ± 32.4	70.4 ± 18.2
	4–4.9	13	15	236.9 ± 24.9	223.0 ± 22.7	13.4 ± 1.4	13.2 ± 1.0	1655.7 ± 584.9	1569.5 ± 450.9	94.9 ± 39.9	94.0 ± 30.0
	>5	10	7	272.0 ± 39.9	257.4 ± 40.3	13.7 ± 0.6	13.2 ± 1.0	1868.9 ± 535.8	1654.8 ± 381.5	94.8 ± 26.8	86.1 ± 21.7
				Peak Force (N)		Relative Peak Force (N·kg^{-1})		Peak Power (W)		Relative Peak Power (W·kg^{-1})	
JMP	<3	7	6	270.1 ± 30.5	266.0 ± 75.7	20.0 ± 2.0	19.7 ± 5.0	69.1 ± 44.2	105.2 ± 104.6	4.9 ± 2.5	7.6 ± 7.5
	3–3.9	11	8	319.2 ± 47.6	331.0 ± 67.7	20.4 ± 2.6	18.7 ± 2.7	98.7 ± 87.4	209.3 ± 158.6	6.1 ± 5.3	12.0 ± 8.1
	4–4.9	13	15	370.9 ± 89.9	359.7 ± 76.0	20.3 ± 3.7	20.7 ± 3.9	203.2 ± 113.1	310.9 ± 354.4	11.1 ± 6.2	18.5 ± 21.7
	>5	10	7	389.9 ± 119.8	389.3 ± 74.8	19.7 ± 6.3	19.6 ± 2.8	599.7 ± 741.0	251.4 ± 191.0	12.3 ± 34.2	28.9 ± 9.2
					Undistracted						
					Sway Amplitude (mm)				Sway Velocity (mm·s^{-1})		
		Un/D	Un/D		M	F			M	F	
BS	<3	3/0	6/5		1.1 ± 1.0	1.1 ± 0.4			10.1 ± 7.6	7.3 ± 3.9	
	3–3.9	10/8	7/6		1.1 ± 0.5	0.7 ± 0.3			7.1 ± 3.9	4.3 ± 1.9	
	4–4.9	12/11	14/13		0.8 ± 0.2	0.6 ± 0.2			5.5 ± 2.2	5.0 ± 2.6	
	>5	8/9	5/5		0.6 ± 0.2	0.7 ± 0.1			5.5 ± 5.0	8.1 ± 2.7	

Mean ± SD.

[a] Surrogate for peak power (slope of the force time curve from 20% to 90% of peak force; Lindemann et al., 2003).

M, male; F, female; Un, undistracted; D, distracted.

TABLE 3. Short-term error (E_{ST}) and learning error (E_{LE}).

Test	Variable	E_{ST}	E_{LE}
STS	Peak force	3.7 ± 2.8	−0.7 ± 4.8
	Relative peak force	1.4 ± 1.1	1.3 ± 7.7
	Peak power	17.7 ± 15.4	5.1 ± 27.5
	Relative peak power	4.5 ± 4.3	7.4 ± 29.7
JMP	Peak force	13.6 ± 13.1	13.7 ± 18.9
	Relative peak force	13.8 ± 13.7	15.6 ± 30.7
	Peak power	33.9 ± 20.5	27.9 ± 44.4
	Relative peak power	35.7 ± 21.2	30.7 ± 46.2
BS undistracted	Sway amplitude	33.2 ± 14.7	11.6 ± 39.2
	Sway velocity	29.5 ± 10.0	5.2 ± 34.4

Values are mean ± SD.

(undistracted only, distracted testing was inconsistent). Exploratory analyses by ANOVA (sex and age) and bivariate correlations (with quantitative predictors) were used to examine the data. Then backward stepwise variable selection was used to identify predictors for multivariate modeling. Normality of each outcome variable was tested by visual examination. In Table 2, data are presented as mean ± SD. Multicollinearity and model assumptions were tested by standard *post hoc* methods. Outcome data (JMP peak power [PP]) were log transformed when necessary. All analyses were performed using SAS (v9.2, Cary, NC). Significance was set at $P < 0.05$.

RESULTS

The study population consisted of 81 healthy preschool-age children from the Greater Montreal area (Table 1). Seventy-one of the 81 children were between the 5th and 95th percentiles for BMI; only one was below the 5th percentile, whereas nine were above the 95th percentile. The mean 25(OH)D concentration across all children was 83.5 ± 28.7 nmol·L^{-1}, suggesting most children had a robust vitamin D status, because only 11.1% had a vitamin D concentration below 50 nmol·L^{-1} (9 out of 81 children). The mean PTH and iCa concentrations across all children were 1.12 ± 0.45 pmol·L^{-1} and 1.29 ± 0.04 mmol·L^{-1}, respectively.

Muscle function data by sex are presented in Table 2. Exploratory analysis using ANOVA demonstrated no sex effect for all measures performed. However, there was an age effect; body mass (proxy for lean mass) appeared to almost completely normalize the results for JMP peak force and nearly completely normalize STS peak force (Table 2). In contrast, peak power in both maneuvers continued to increase with age despite normalization for body mass. These results were used to develop regression models to more thoroughly evaluate potential variables accounting for a large amount of the variation in the lower-extremity muscle function tests. Detailed assessment of distracted BS testing was omitted because of consistently poor performance: children often fidgeted while being asked questions, making it difficult to assess pure BS during periods of mental concentration.

Reproducibility. Nine children performed all maneuvers twice for calculation of reproducibility (short-term error and learning effect). The STS test had the greatest reproducibility (Table 3) with low E_{ST} for peak force (1.4%–3.7%). JMP peak force was reasonably reproducible (E_{ST} approximately 13%). In both JMP and STS maneuvers, peak power is an indirect (calculated) assessment and had considerably more variability (E_{ST}, 17%–34%) than direct measurement of peak force, although STS PP is improved when considering the body mass of the child (5%); JMP PP is still more variable (36%). Undistracted BS had an unacceptably large E_{ST} (approximately 30%). These tests were performed across all ages (2 yr, $n = 1$; 3 yr, $n = 3$; 4 yr, $n = 5$; 5 yr, $n = 0$). There was no learning effect found, as E_{LE} (Table 3) was not significantly different from 0. As regards CV (Table 4), peak force from STS and JMP appeared to have the lowest variability, whereas PP from both STS and JMP as well as results from the BS tests demonstrate a much higher CV. From our observations of the children undertaking these procedures, it was clear that several tasks were almost universally well completed, such as STS, which reproduces a natural day-to-day movement. Others such as JMP were attempted with what appeared to be good intention, but often inadequately executed, particularly for young children under 4 yr.

When evaluating the more consistently performed maneuvers in regression models, we found that age (likely a proxy for developmental stage) significantly accounted for a large amount of the variation for all models (Table 5). Not only was STS peak force the most reproducible of the procedures, but our regression model also fits the data the best. Age was an important positively associated variable accounting for a significant amount of the variation in STS

TABLE 4. CV for muscle function output for sit-to-stand, jump, and BS.

Test	Age	Peak Force (%)	Relative Peak Force (%)	Peak Power (%)	Relative Peak Power (%)
STS	<3	13.0	7.9	59.7	61.5
	3–3.9	24.1	19.0	47.2	45.6
	4–4.9	10.8	9.3	32.2	37.1
	≥5	14.9	6.1	26.8	26.8
JMP	<3	19.9	17.9	89.5	86.3
	3–3.9	18.4	13.4	87.1	80.3
	4–4.9	22.6	18.3	105.4	111.6
	≥5	25.9	25.5	130.4	124.9
			Undistracted		
			Sway Velocity	Sway Amplitude	
BS	<3		29.4	61.9	
	3–3.9		45.7	65.8	
	4–4.9		30.4	45.8	
	≥5		22.7	67.2	

TABLE 5. Full multiple linear regression models for muscle function.

Parameter	Regression Coefficient	P Value	95% CI
STS peak force		R^2 = 0.859	
Intercept	−36.542		−64.507 to −8.577
Age (yr)	12.949	0.001*	6.415 to 19.482
Lean mass (kg)	14.087	0.001*	10.446 to 16.071
Fat mass (kg)	9.284	0.001*	4.566 to 14.002
STS peak power		R^2 = 0.353	
Intercept	−143.387		−644.224 to 357.452
Age (yr)	363.500	0.001*	246.824 to 480.176
BAZ	139.946	0.043*	4.531 to 275.361
JMP peak power		R^2 = 0.404	
Intercept	38.474		8.393 to 176.408
Age (yr)	1.888	0.001*	1.514 to 2.353
25(OH)D ($\text{nmol}\cdot\text{L}^{-1}$)	0.994	0.111	0.987 to 1.001
BAZ	1.649	0.001*	1.225 to 2.222
Fat mass (kg)	0.999	0.143	0.999 to 1.000
BS undistracted amplitude		R^2 = 0.348	
Intercept	3.498		1.281 to 5.716
Age (yr)	−0.250	0.001*	−0.368 to −0.132
25(OH)D ($\text{nmol}\cdot\text{L}^{-1}$)	−0.002	0.174	−0.004 to 0.001
BAZ	−0.082	0.069	−0.171 to 0.007
iCa ($\text{mmol}\cdot\text{L}^{-1}$)	−1.503	0.071	−3.142 to 0.136
Lean mass (kg)	0.036	0.134	−0.000 to 0.001

peak force after adjusting for all other variables (regression coefficient (β) = 12.949; 95% confidence interval (CI), 6.415–19.482, P = 0.001). Moreover, lean and fat mass (Table 5) also positively contributed to the model (lean mass, β = 14.087, 95% CI, 10.446–16.071, P = 0.001; and fat mass, β = 9.284, 95% CI, 4.566–14.002, P = 0.001) and were similar in magnitude to age.

For STS peak power (moderately reproducible with E_{ST} approximately 5%–18%), age again accounted for a significant amount of the variation in the full model (β = 363.500; 95% CI, 246.824–480.176, P = 0.001; Table 5), whereas BAZ was also important (β = 139.946; 95% CI, 4.531–275.361, P = 0.043; Table 5). No other variable was statistically significant. Normalizing JMP peak force for body mass (Table 2) fully accounted for the observed age differences. For JMP peak power, age accounted for a significant amount of the variation in the full model (β = 1.888; 95% CI, 1.514–2.353, P = 0.001; Table 5) and BAZ was also important and similar in magnitude to age (β = 1.649; 95% CI, 1.225–2.222, P = 0.001; Table 5); Lastly, age was the only important variable accounting for a significant amount of the variation in undistracted BS amplitude (β = −0.250; 95% CI, −0.368 to −0.132, P = 0.001; Table 5). The model accounted for only a moderate portion of the variability (R^2 = 0.348), similar to JMP peak power (R^2 = 0.404) and STS peak power (R^2= 0.353).

DISCUSSION

This study provides new insights into the utility of force plate measurements in very young children. We have provided normative data for three separate maneuvers, demonstrating no sex effects for any of the tests. This is in keeping with the results in older children performing jumps (14,33). To the best of our knowledge, no other pediatric manuscript has examined such a large number of children across all three maneuvers. The STS maneuver was by far the most reproducible in children age 24–72 months of age, likely reflecting that this is a commonly performed activity, such as rising from a chair (6). Our E_{ST} for peak force were under 4%, and our CV was less than 24%, which is similar to the variation observed in 13 children age 7–11 yr (39).

Few studies have examined the variables important to perform these maneuvers beyond age and body mass. Certainly increasing body mass has been associated with increased peak force and power in pediatrics (14,33,39). Using data from DXA to generate lean and fat mass as well as blood tests for mineral and calcitropic hormone status, we have determined that age—a proxy for developmental stage—was very important in all models as well as some measure of body mass (BMI *z*-score or lean or fat mass). None of the biochemical variables such as 25(OH)D, PTH, or ionized calcium concentrations or the effect of sex were not important predictors in any of the models. For the STS peak force assessment, age lean and fat mass were all positively associated with comparable effect sizes. For both STS peak power and JMP peak power, BAZ (BMI-*z*-score) was also positively associated with these maneuvers. BMI may be interpreted as a proxy for mechanical load and resulting strength, although we did not measure these directly.

The JMP procedure was moderately well performed, and our reproducibility was slightly worse compared with that observed in children age 7–11 yr (39) and 6–19 yr (14). Given typical development, we had anticipated that children under 4 yr would not be able to perform a double-leg jump well, consistent with the greater variation in peak force during this maneuver. Given the modest number of children who repeated the procedures, we cannot determine whether the older children measured could have performed these tasks with less variability then the younger children, although we suspect this is the case based on our observations.

In both maneuvers, peak power is an indirect measurement requiring either numerical integration (JMP) or surrogate measurement of the slope of the force versus time relation (STS). This may explain why variability is much higher than that seen in peak force measurements, although this is not consistently observed across other pediatric studies (14,33,39). Interestingly, peak forces in both JMP and STS testing were almost completely normalized by body mass in Table 2. In contrast, peak power continued to increase with age despite correction for body mass, suggesting enhanced muscle development, postural tone, or coordination in older children.

As expected, increasing age was the only variable negatively associated with undistracted BS. Again, most research has assessed BS in small numbers of children (n = 10) without detailed assessment of determinants(3,7). By observation, our younger children had a more challenging time standing still on the force plate for 30 s. Perhaps having children stand for a shorter duration, sit on a chair on the force plate, or sit directly on the plate as described in other infants might reduce variability (15,16). We did not find any association with vitamin D status in these healthy children.

This is unlike the finding by Pfeifer et al. (28) demonstrating that adults with vitamin D deficiency had a 9% decrease in sway with vitamin D supplementation. Most of our cohort had robust 25(OH)D status, likely limiting our ability to detect differences. To increase BS, we first attempted to have the children stand with their eyes closed; almost all children piloting this study refused to do so. We then attempted distraction using questioning, which created fidgeting and movement by most children, limiting the utility of the distracted maneuver. It is no surprise that distracted BS testing was particularly poorly performed given the obvious fidgeting during the procedure. Our observation of the children during these tests combined with the large variability in the measures implies that standing postural control assessments of BS are invalid in young preschool-age children.

Improvements in the motor control of muscle function begin as children gradually develop coordination of muscles involved in the movement being performed, which is known as functional synergy (34,42). This development of force-modulation skills and motor control (30) allows children to elicit greater degrees of muscle function and postural control. The current data suggest that simple functional tasks performed on a force platform can be used to measure muscle function and the development of postural control. In this regard, age is the most important variable in this development across all tasks performed in the current study.

Previous research has suggested that although age is an inherent contributor to muscle function during physical tasks, experience performing motor tasks and ability to interact and coordinate other external stimuli also play an important role (30). We did not have validated measures of development, such as the Peabody Developmental Motor Scales, nor did we have data on activities such as gymnastics classes that could have confounded "age." These assessments might be important in our regression models.

The strengths of our study include the assessment of a large number of preschool-age children and a wide range of maneuvers. In addition, we determined reproducibility for all procedures, and the STS test was by far the easiest for the children to perform and the most reliable measure. Unlike other pediatric studies, we had body composition (i.e., lean mass) and calcitropic hormone concentrations to assess as predictors in addition to other anthropometric measures such as height, body mass, and head circumference. One observer (T. H.) performed all the studies, and the reliability (E_{ST}, 3.72 ± 2.83) was good. For ease of application, our customized software automatically calculated force, power, and sway amplitude.

Additional studies may wish to formally grade the ability of the child to perform the maneuvers and use this measure in regression models to see if "quality of performance" explains some of the residual variability (14,33,39). Future work should limit some procedures such as the two-legged jump to older children (age 4 yr or more) and perhaps adapt BS assessment for very young children (sitting on a chair on the force plate or sitting directly on the force plate). The current study focused on the reproducibility of the "best" (1) rather than the "average" (20) performance, consistent with recent force plate studies in children (14,33,39) and with theoretical studies suggesting that this is a more reproducible measure when intraindividual variability is high (1). Nevertheless, the use of both the "best" (10,14,22,33,35, 37,39,40) and "average" (10,11,25) performances continues to appear in the literature with some frequency, suggesting that the issue remains unresolved (1). The reported coefficients of variation suggest that the STS test is more reproducible than JMP or BS for children in this age range. Moreover, as with other force plates and software, indirect measurements calculated from primary force outputs (e.g., power) add some uncertainty and likely contribute to the higher CV. The data in the present study can be used as a basis for further development of normative data evaluating leg muscle function and postural control in larger cohorts of preschool-age children.

CONCLUSION

This is likely the first large-scale pediatric assessment of various maneuvers using a force plate. The reference data demonstrate a very clear age (developmental) effect without any effect of sex. Lean mass, likely a proxy for strength, is deemed important in one model (STS peak force), whereas body size (BAZ) is similarly important in two models (STS and JMP peak power). Body mass also completely normalizes some differences in peak force, suggesting less of a developmental effect. The STS procedure is clearly the best of the three maneuvers and can easily be administered even to very young children. We anticipate that additional larger cohorts will be assessed to further validate these reference data.

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