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Rapid Force Generation is Impaired in Cerebral Palsy and is Related to Decreased Muscle Size and Functional Mobility

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Abstract

Limb movements involving contraction times of 50–200ms occur in many everyday activities, such as gait, which is faster than the time required to generate maximal force. Therefore, the ability to rapidly produce force may be even more important for the performance of functional activities. In this study rate of force development (RFD) and impulse of the knee extensors were examined in 12 ambulatory children with cerebral palsy (CP) (Age: 11.9 ± 2.9 yrs) and 11 with typical development (TD) (Age: 11.3 ± 3.0 yrs). The relationship with muscle architecture and functional mobility was also determined. RFD and impulse were calculated during a maximal isometric knee extension contraction. Rectus femoris (RF) cross-sectional area and RF and vastus lateralis (VL) muscle thickness (MT), fascicle length (FL), and fascicle angle (FA) were measured using ultrasound imaging. Gait temporal-spatial parameters, Pediatric Outcomes Data Collection Instrument (PODCI), and Activities Scale for Kids performane version (ASKp) were collected. Although VL MT was the primary determinant of RFD and impulse in CP, FA and FL were also significant predictors in the TD group. RFD and impulse were significantly lower in CP compared to TD (70% decrease) in addition to maximal strength (50% decrease). RFD and impulse were predictive of measures of functional mobility, including gait, transfers, and sports and higher level activities but not temporal-spatial gait measures. Results suggest that the ability to rapidly generate torque may be of greater importance than maximal strength during certain tasks, such as transfers and sports and higher level activities.

Introduction

Cerebral palsy (CP) is characterized by motor impairments such as muscle weakness, spasticity, stiffness, and excessive cocontraction.¹ However, only weak to modest relationships between spasticity and stiffness with function have been observed in the literature.^{2, 3} On the other hand muscle strength, particularly of the quadriceps, has consistently been reported to be highly correlated to gross motor function as assessed by the Gross Motor Function Measure (GMFM) ($r = 0.70$ to 0.83).^{2, 4} The rate at which force or torque is produced, known as the rate of force development (RFD) and the area under the

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torque-time curve, known as contractile impulse, are important temporal parameters of force production that have often been overlooked in CP. It typically takes over 300 ms to achieve maximal force in most human muscles.⁵ However, everyday activities often involve faster limb movements with contraction times of 50–200 ms.⁶ Therefore, time-dependent measures of force production should be considered in addition to absolute measures (i.e. maximal force) to adequately characterize performance of everyday activities.

During normal gait, the quadriceps begin to fire in terminal swing in order to stabilize the knee in extension for initial contact. However, increased knee flexion at initial contact throughout stance is a common gait characteristic in CP.^{7, 8} The first period of double support in the gait cycle is termed “loading response”. During normal walking, quadriceps activity peaks in loading response and requires force to be generated within approximately 150 ms in order to move the ground reaction force anteriorly to the knee joint axis to achieve knee extension.⁹ Considering that it typically takes greater than 300 ms to reach maximal force, the RFD of the quadriceps may be the key limiting factor rather than maximal strength during gait in children with CP. Furthermore, most functional activities of daily living such as walking do not require maximal strength¹⁰ despite that the percentage of maximum required in CP may be higher than their peers with typical development (TD).¹¹ As a result, the temporal characteristics of force generation may be more important for functional activities than maximal strength.

Time dependent parameters of muscle contraction, such as RFD and impulse, may be influenced by neuromuscular factors including fiber type, muscle strength, motor neuron recruitment, and firing rate as well as by muscle architecture, all of which have been shown to be impaired in CP.^{2, 12–16} In particular, RFD is influenced by muscle size, which is related to the number of sarcomeres in parallel.^{17, 18} Because the shortening velocity of a muscle is dependent on the number of sarcomeres in series, fascicle or fiber length may also be an important determinant. A greater shortening velocity secondary to longer fascicle lengths would allow greater force generation compared to a muscle with shorter fascicles at an identical shortening velocity.^{18, 19}

Therefore, the purpose of this study was to examine the RFD and impulse characteristics of the knee extensors in children with CP and those with TD and to determine which muscle architectural parameters were predictive of RFD and impulse. We also sought to determine the relationships between RFD, impulse, and strength of the knee extensors with temporal-spatial gait parameters and self-reported measures of functional mobility in those with CP. We hypothesized that RFD and impulse would be decreased in CP as compared to TD but would have similar relationships to muscle architecture. We also hypothesized that RFD would be more predictive of gait parameters and functional mobility than strength.

Methods

PARTICIPANTS

Twelve ambulatory children with spastic CP (mean age = 11.9 ± 2.9 years) and 11 with TD (mean age: 11.3 ± 3.0 years) participated in this prospective study. Participants with CP were within Gross Motor Function Classification System (GMFCS) Levels I ($n = 4$), II ($n = 2$), and III ($n = 6$) and were diagnosed with spastic diplegia. Those who underwent orthopedic or neurosurgery within six months prior to testing or Botulinum toxin injections to the quadriceps within three months prior to the testing were excluded from the study. The study was approved by the Institutional Review Board at our institution, and written parental consent and child assent were obtained.

PROCEDURES

Ultrasound—Ultrasound images (Voluson 730 Expert, GE Healthcare, Kretztechnik, Zipf, Austria) were recorded in real-time using a 6–12 Mhz linear array transducer in 2D B-Mode. The right lower extremity was chosen for measurement. Participants were positioned in supine with the knee joint near the natural resting position of 10 degrees. Images were only recorded when the muscle was fully relaxed as evidenced through real-time scanning. Images of the rectus femoris (RF) were taken at 50% of the distance between the anterior superior iliac spine and the superior border of the patella, and vastus lateralis (VL) images were taken at the midpoint between the most prominent portion of the greater trochanter and lateral femoral epicondyle. Each midpoint was clearly marked on the skin with a surgical pen. A generous amount of gel was applied to the skin to aid acoustic transmission and minimize compression of skin. A more detailed description of methods and an illustration can be found elsewhere.¹² Images were taken with the probe oriented longitudinally, and the following measurements were calculated: 1) muscle thickness (MT) as the distance between the superficial and deep aponeuroses in the middle of the ultrasound image at a 90° angle from the deep aponeurosis, 2) fascicle angle (FA) as the positive angle in degrees between the deep aponeurosis and the line of the fascicle, and 3) fascicle length was estimated as $MT/\sin(FA)$.¹⁶ Using a 3D volume probe, images were taken with the probe oriented transversely, and anatomical cross-sectional area (CSA) of the RF was calculated at the same landmark as above. Three images were taken per muscle, and the average value from the three images for each measurement was used for the analyses. Using this protocol, intrasession reliability was previously reported to be high for all measures (CP: ICC 0.93 – 0.98; TD: ICC 0.88 – 0.98).¹²

Isometric testing—Each participant was seated in an isokinetic dynamometer (System 3 Pro, Biodex Medical Systems, Shirley, NY) with a trunk flexion angle of 85 degrees from the horizontal. Stabilizing straps at the trunk, pelvis, and thigh were used to minimize extraneous movements and substitutions. The knee joint was aligned with the axis of the dynamometer and the knee positioned at a knee angle of 60 degrees of flexion. Each participant performed three maximum voluntary isometric contractions (MVIC). The participants were instructed to kick (into extension) “as hard and fast as possible.” Each MVIC was sustained for approximately 3 seconds with a 60 second rest in between trials. Data were collected for a total of 5 seconds per trial. Trials with initial counter movements, counter movements during the sustained portion of the trial, or absence of a quiescent baseline force reading prior to contraction were discarded.²⁰ The retained trial with the highest MVIC was used for analysis.

For data analysis, moment data were gravity corrected. The onset of contraction was determined when the torque reached 2.5% of the MVIC for each participant.²¹ RFD was calculated as the average slope over the moment-time curves ($\Delta\text{moment}/\Delta\text{time}$) between 0–30, 0–50, 0–100, and 0–200ms relative to the onset of contraction. Peak RFD (PRFD) was calculated as the maximum slope during the 0–200ms time period and RFD_{50} was calculated as the slope at the level of 50% of MVIC. Impulse was calculated as the area under the moment-time curve ($\int \text{Moment } dt$) at the same time intervals between 0–30, 0–50, 0–100, and 0–200ms relative to the onset of contraction. Impulse is directly proportional to the angular velocity of the limb, providing additional information regarding the time history of muscle contraction.²⁰ The peak isometric moment (MVIC) was normalized to body mass ($\text{N}\cdot\text{m}\cdot\text{kg}^{-1}$).

Gait Parameters—Temporal-spatial gait parameters were collected using a Vicon motion capture system (Vicon, Oxford Metrics, Oxford, UK) over level ground at a self-selected walking velocity and included velocity, cadence, step length, and stride length. Temporal-

spatial gait parameters were also collected at a fast walking velocity. Three trials were analyzed per walking condition, and a representative trial was used for analysis.

Functional Assessments—Functional mobility was measured with the Pediatric Outcomes Data Collection Instrument (PODCI) parent report and the Activities Scale for Kids Performance version (ASKp). The PODCI measures self-reported physical function and psychosocial aspects of health status in children with mild to moderate musculoskeletal disability.²² The following scales were used for analysis: Transfers and Basic Mobility and Sports/Physical Functioning Scales. The ASK is a reliable, valid and responsive child self-report measure of physical disability (Young & Young).²³ The following sub-domains of the ASKp were used for analysis: Locomotion, Standing Skills, and Transfers.

Statistical Analysis—Group comparisons of RFD and impulse data (CP and TD) were performed using independent t-tests. Multiple regression analysis was used to determine which muscle architectural parameters were most predictive of RFD and Impulse, separately for those with CP and TD. Muscle architectural variables were entered individually into the models to determine which variables were statistically significant. Next, control variables (age, height, and weight) were entered to determine which ones improved the predictive value of the models. Finally, combinations of significant variables were entered to determine the best models. If the addition of a variable resulted in a P value < 0.05 , then the variable was kept in the model and the next variable entered. Regression analyses were also used to determine the predictive relationships between RFD, impulse, and MVIC with gait parameters and self-reported measures of functional mobility.

Results

RFD and Impulse

Knee extensor RFD and impulse values in the group with CP were all significantly lower than those with TD ($p = 0.001 - 0.002$). Figures 1a and 1b illustrate means and standard deviations for RFD and impulse parameters, respectively. On average, RFD and impulse were 70% lower in CP compared to the TD group (range: 64% to 76%). MVC normalized by body mass ($\text{Nm}\cdot\text{kg}^{-1}$) was 50% lower in CP compared to TD (CP: $1.03 \pm .55$; TD: $2.02 \pm .52$; $p = 0.001$).

In order to examine differences in RFD between groups, independent of differences in strength, RFD was normalized to each subject's MVIC for a separate analysis. Significant differences between the TD and CP groups remained for normalized RFD at 0–30, 0–50, and 0–100ms relative to onset of contraction ($p = 0.01$ to 0.02). However, there were no significant differences for normalized 0–200ms, PRFD, OR RFD₅₀ ($p = 0.054$ to 0.64).

Muscle Architecture

Means and standard deviations (SD) of muscle architectural variables are given in Table 1. Regression analyses revealed similar relationships across all time intervals of RFD and impulse outcomes measures. Therefore, only PRFD and Impulse (0–100) were reported here as representative measures. For CP, the only significant predictor of PRFD and Impulse (0–100) was VL MT (PRFD: $R^2 = 0.35$; Impulse: $R^2 = 0.50$). The addition of control variables (height, weight, age) or other muscle architectural variables did not significantly improve the models.

For the TD group, all muscle architectural variables were significant predictors of PRFD and Impulse (0–100). R^2 values ranged from 0.46 to 0.71 for PRFD and from 0.37 to 0.70 for Impulse (0–100). The combination of VL MT and RF FL and the combination of VL MT

and RF FA were significant predictors of PRFD with R^2 values of 0.85 and 0.82, respectively. For Impulse (0–100), the combination of RF MT and RF FL and the combination of RF MT and RF FA were significant predictors with R^2 values of 0.73 and 0.80, respectively. Results from the final models of the multiple regression analyses for PRFD and Impulse (0–100), respectively, are given in Tables 2 and 3.

Relationships with Gait and Functional Mobility in CP

PRFD, RFD₅₀, and Impulse (0–100) were reported here as representative measures. MVIC, RFD, and Impulse were not associated with any of the kinematic or temporal-spatial variables ($r = -0.60$ to 0.62 ; $p = 0.054$ to 0.863). In addition, MVIC was not significantly associated with RFD or Impulse but approached significance (Table 4). As reported in Table 4, PRFD, RFD₅₀, and Impulse (0–100) showed significant relationships with all of the ASKp domains and PODCI subscales analyzed here. Independently, PRFD and Impulse were the strongest predictors of PODCI Sports and Physical Functioning ($r = 0.82$; $R^2 = 0.67$), indicating the importance of time dependent contractile characteristics of the knee extensors for gait and higher level physical functioning. MVIC showed similar relationships with ASKp domains and PODCI subscales, except for ASKp Transfers and PODCI Transfers and Basic Mobility, which were not statistically significant. The linear combination of PRFD and MVIC was the strongest predictor of PODCI Sports and Physical Functioning and ASKp Locomotion, explaining a total of 78% and 77% of the variance, respectively. To determine whether PRFD was a better predictor than MVIC, we removed each variable from the model to determine whether the change in the R^2 value was significant. The removal of PRFD from the model for PODCI Sports and Physical Functioning significantly reduced the R^2 value from 0.78 to 0.50 ($p = 0.01$). However, the removal of MVIC did not significantly affect the model, reducing the R^2 value from 0.78 to 0.66 ($p = 0.06$), indicating that PRFD is the better predictor of sports and higher level activities. In contrast, the removal of PRFD from the model for ASKp Locomotion did not significantly reduce the R^2 value ($p = 0.21$; decreased from 0.77 to 0.72) whereas the removal of MVIC did significantly reduce the predictive value of the model from 0.77 to 0.38 ($p < 0.001$). This indicates that MVIC is the better predictor for self-reported gait ability.

Discussion

Consistent with our hypotheses, RFD and impulse of the knee extensors were 70% lower in our participants with CP compared to the TD group averaged across all time intervals. RFD and Impulse were predictive of all measures of functional mobility as assessed through the PODCI and ASKp. RFD was also a better predictor of sports and physical functioning as compared to strength. Furthermore, RFD and Impulse were unique predictors of the ability to perform transfers (ASKp and PODCI). However, these parameters demonstrated no relationship with temporal-spatial features of gait.

RFD and impulse were influenced by different muscle architectural parameters in the participants with CP as compared to the TD group. VL MT alone explained 35% and 50% of the variance in RFD and impulse, respectively. Perhaps decreased MT of the RF and VL reported in Table 1 and previously reported in children and adolescents with CP^{12, 24} has a more detrimental effect on RFD than other architectural parameters as it believed that increases in muscle size are primarily responsible for increases in RFD following strength training due to greater numbers of sarcomeres in parallel.¹⁷ For the TD group, all muscle architectural variables were significant predictors with a combination of variables explaining 73% to 85% of the variance in impulse and RFD. The results for the TD group are in line with studies in healthy adults, where muscle architecture has been associated with increases in RFD.^{17, 18} In our study, RF FL was positively associated with RFD and Impulse in those

with TD, where FA was negatively associated. An increase in the number of sarcomeres in series as indicated by fascicle length would allow for a greater fiber shortening velocity, which would have a direct influence on RFD and impulse.

Time dependent characteristics of muscle contraction are influenced by muscle architecture as well as a number of neuromuscular factors, such as fiber type, muscle strength, cocontraction, motor neuron recruitment, and firing rate, etc.⁶ Fiber type alterations, muscle weakness, excessive cocontraction of the hamstrings, and impairments in motor unit recruitment and rate modulation have also been observed in CP.^{2, 13–15} In particular, the predominance of Type I fibers that has been reported in CP may contribute to the decreased RFD as the shortening velocity of slow twitch fibers is 25% less than that of fast twitch.²⁵ Tammik et al.²⁶ reported a 64% reduction in RFD₅₀ compared to a group of children with TD. Our findings are similar to Tammik et al. with a 64.5% decrease in RFD₅₀ specifically and an average decrease of 70% across all time intervals of RFD measurement. The results for RFD normalized by MVIC indicate that strength explains a significant portion of the differences in RFD observed between groups when the time from onset of contraction is extended (0–200ms, RFD₅₀, and PRFD). At onset times < 100ms, intrinsic contractile properties of the muscle are primarily responsible for group differences. These findings are consistent with other studies that have shown that RFD is more closely related to strength during the later phases of rising muscle force.²⁷

RFD, impulse, and strength of the knee extensors were strong predictors of sports and physical functioning as assessed with the PODCI. However, RFD was a better predictor as compared to strength. Sports and higher functioning activities require higher velocity movements in which force needs to be generated rapidly. This may explain why RFD was more strongly associated with the PODCI Sports and Physical Functioning scale than strength.

Interestingly, RFD and impulse were strongly associated with the ASKp and PODCI transfer scales, but strength was not. Rapid development of quadriceps torque may be necessary for transfers, such as going from sit to stand or getting on and off of the floor. Moreover, there may be particular time constraints associated with the RFD. In healthy adults, only approximately 40% of maximal knee extensor strength is required for going from sit to stand.²⁸ Although this percentage may be higher in children with CP, the ability to generate higher rates of torque within the first 200 ms of the movement may be of greater importance for these types of tasks than maximal strength if the percentage requirement of maximal strength remains lower than 100%.

RFD, impulse, and strength were significant predictors of locomotion as assessed with the ASKp, but were not predictive of temporal-spatial gait parameters, such as velocity, cadence, step, and stride lengths. These differences are most likely due to the nature of the measures (self-reported locomotor function versus specific measures of temporal-spatial parameters during self-selected walking). Although strength was determined to be a better predictor of ASKp Locomotion than RFD, the combination of strength and RFD of the knee extensors alone explained 77% of the variance in overall gait function.

In healthy children, maximal quadriceps strength is 2.3 times greater what is required during gait.¹⁰ Considering that quadriceps force must be produced within approximately 150 ms during loading response in normal gait, perhaps non-operative interventions aimed at improving gait in children with CP should focus not only on improving knee extensor strength but also on improving the rate in which knee extensor force is developed. For example, increased knee flexion in stance, or crouch, is a common gait characteristic in children with CP that tends to worsen over time as the child ages.⁷ Hamstring lengthenings

are often performed to counteract this impairment with varied success, depending on the amount of crouch preoperatively.⁸ Quadriceps strengthening has also been proposed to improve knee flexion in stance. In a study by Damiano et al.²⁹, quadriceps strengthening in children with CP resulted in an improvement in the amount of knee flexion at initial contact but did not improve the amount of knee flexion in mid stance. Although strength is positively associated with RFD, traditional resistance training (slow, controlled movements) has been shown to affect late RFD only (0–250ms).³⁰ Training at higher velocities of movement may result in greater RFD at earlier time intervals (< 250ms) and therefore, be more beneficial in improving the amount of knee flexion in stance than traditional strength training. This would allow a higher level of force to be reached within the critical early phase of quadriceps muscle contraction during gait (0–150ms), thus affecting the degree of knee flexion throughout stance.²⁰ Increases in RFD at later time intervals have been observed after resistance training performed at high movement velocities (or explosively) with both light¹⁸ and heavy loads.³¹ However, the effect of high velocity training on RFD at earlier time intervals has not been investigated as extensively and needs further exploration.³²

To our knowledge, this is the first report of contractile impulse in the CP population. Impulse as defined by $\int \text{Moment } dt$ is the equivalent of kinetic impulse or momentum during contractions where the limb was allowed to move. Kinetic impulse is defined by $I \cdot \omega$, where I is the moment of inertia of the limb and ω is the instantaneous rotational velocity of the limb. Therefore, the magnitude of the impulse would determine the angular velocity of the limb if it had been allowed to move.²⁰ According to Aagaard et al.²⁰, impulse is the single most important strength parameter because it reflects the entire time history of contraction, including RFD, by measuring the entire area of the moment-time curve. Our results indicate that this important time dependent characteristic was predictive of all measures of functional mobility as assessed through the PODCI and ASKp. Limitations of our study are that we did not have an adequate sample size to adjust for height, weight, and GMFCS levels and did not correct for multiple comparisons.

In summary, time dependent force characteristics of the knee extensors were significantly impaired in CP and were associated with measures of functional mobility, including gait, transfers, and sports and higher level activities. Although VL MT was the primary determinant of RFD and impulse in our participants with CP, other muscle architectural parameters, such as FA and FL were important predictors in the TD group. This study highlights the importance of time dependent characteristics of force production and the need to focus interventions in CP on the ability to rapidly produce movements rather than solely on the ability to produce high levels of force.

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Figure 1.

RFD measures (mean $\pm$ SD) in the CP and TD groups are illustrated in Figure 1a. Impulse measures (mean $\pm$ SD) in the CP and TD groups are illustrated in Figure 1b. Differences between groups were statistically significant ($p < 0.05$).

Table 1

Means and standard deviation (SD) for muscle architectural variables

	CP	TD	<i>p</i> value
RF CSA (cm ²)	4.10 (1.48)	7.58 (1.88)	<.001
RF muscle thickness(cm)	1.40 (0.31)	2.02 (0.31)	<.001
RF fascicle length (cm)	7.45 (2.00)	9.95 (2.29)	.011
RF fascicle angle (°)	11.41 (3.44)	12.32 (3.45)	.533
VL muscle thickness(cm)	1.21 (0.41)	1.80 (0.63)	.014
VL fascicle length (cm)	6.78 (2.59)	7.63 (1.20)	.321
VL fascicle angle (°)	11.04 (3.32)	13.57 (3.08)	.073

Table 2

Multiple linear regression analysis of the prediction of RFD from RF and VL muscle architecture for the CP and TD groups

Group	Variables	Beta coefficient	Standard error	p	Model R-square
CP	Intercept	-0.06	0.10	0.555	0.35
	VL MT (mm)	18.49	7.89	0.041	
TD	Intercept	-0.44	0.15	0.023	0.85
	VL MT (mm)	26.04	5.80	0.002	
	RF FL (mm)	4.25	1.60	0.029	
TD	Intercept	0.15	0.16	0.37	0.82
	VL MT (mm)	33.15	5.68	<0.001	
	RF FA (degrees)	-23.84	10.37	0.05	

CP = cerebral palsy; TD = typically developing; PRFD = peak rate of force development; VL = vastus lateralis; RF = rectus femoris; MT = muscle thickness; FL = fascicle length; FA = fascicle angle

Multiple linear regression analysis of the prediction of Impulse (0–100ms) from RF and VL muscle architecture for the CP and TD groups

Table 3

Group	Variables	Beta coefficient	Standard error	p	Model R-square
CP	Intercept	−410.3	341.02	0.257	0.50
	VL MT (mm)	0.083	0.027	0.011	
TD	Intercept	−5156.8	1610.6	0.013	0.73
	RF MT (mm)	0.238	0.074	0.013	
	RF FL (mm)	0.025	0.01	0.039	
TD	Intercept	−2584.9	1305.9	0.083	0.80
	RF MT (mm)	0.351	0.066	<0.001	
	RF FA (degrees)	−0.195	0.059	0.011	

CP = cerebral palsy; TD = typically developing; RF = rectus femoris; MT = muscle thickness; FL = fascicle length; FA = fascicle angle

Table 4

Linear regression coefficients (r) for relationship between MVIC, PRFD, RFD₅₀, and Impulse (0–100 ms) and measures of functional mobility

	PODCI Sports Phys. Function	PODCI Transfers	ASKp Transfers	ASKp Locomotion	ASKp Standing	MVIC (N·m/kg)
PRFD	0.82* (p=.001)	0.58* (p=.047)	0.66* (p=.03)	0.62* (p=.03)	0.71* (p=.01)	0.51 (p=.09)
RFD ₅₀	0.79* (p=.002)	0.61* (p=.04)	0.69* (p=.02)	0.59* (p=.04)	0.67* (p=.02)	0.46 (p=.14)
Impulse (0–100ms)	0.82* (p=.001)	0.60* (p=.04)	0.63* (p=.04)	0.68* (p=.02)	0.73* (p=.007)	0.57 (p=.053)
MVIC (N·m/kg)	0.70* (p=.01)	0.57 (p=.053)	0.32 (p=.34)	0.85* (p<.001)	0.68* (p=.02)	1.00

MVIC = maximum voluntary isometric contraction; PRFD = peak rate of force development; RFD₅₀ = rate of force development at 50% of maximum torque; PODCI = Pediatric Outcomes Data Collection Instrument; ASKp = Activities Scale for Kids Performance Version;

* indicates $P < 0.05$