



Full length article

Mechanical work, kinematics, and kinetics during sit-to-stand in children with and without spastic diplegic cerebral palsy

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ABSTRACT

Background: Sit-to-stand (STS) is one of the most common fundamental activity in daily life. The pathology of the neuromuscular control system in children with spastic diplegic cerebral palsy (SDCP) could contribute to atypical movement patterns leading to the inefficiency performance including the STS task. However, there was also a lack of evidence about kinematics, kinetics, and especially mechanical work during the STS task in children with SDCP aged 7–12 years old.

Research question: What were the differences in mechanical work, kinematics and kinetics during STS task between children with SDCP and typically developing (TD) children?

Methods: Eleven children with SDCP (GMFCS I-II) and eleven age and gender-matched control TD children with an age range of 7–12 years were enrolled. Motion analysis and force plate systems were used to collect data. All participants performed the STS task from an adjustable chair. Independent sample *t*-test and two-way analysis of variance were used in this study.

Results: The children with SDCP took a longer time and used more mechanical work during STS than TD children. At the beginning of the STS task, children with SDCP showed more trunk flexion and posterior pelvic tilting; in addition, during the STS task they also presented more trunk, hip, and knee flexion than TD children. However, the children with SDCP showed less ankle dorsiflexion compared with TD children. For the kinetic variables, asymmetry was found in children with SDCP. The maximum hip and knee extension moment, plantar flexion moment, and peak vertical ground reaction force (GRF) of the non-dominant leg were higher than the values of the dominant leg in these children.

Significance: Even though, children with SDCP who are able to independently STS. They were also a mechanically less efficient performance during STS task. Therefore, this task still needs to be trained during rehabilitation sessions.

1. Introduction

Cerebral palsy (CP) is a group of permanent disorders in children. It is caused by a non-progressive brain injury or malformation in the brain that arose in the developing fetus or infant [1]. The most common type of CP is spastic diplegic CP (SDCP) [2]. These children present with muscle weakness [3], lack of muscle coordination [4], and poor balance, postural control and postural alignment [5,6]. These impairments can contribute to deviations of movement patterns leading to inefficiency of performance and the increasing energy expenditure while performing functional activities [7,8]. One of the simplest functional activities that children perform many times each day is standing up from a chair.

The sit-to-stand (STS) task has been reported as the most common fundamental activity in daily life [9]. The ability to perform this task is a prerequisite for other activities of daily living such as walking [10]. The STS task is a demanding biomechanical task since it requires the coordination of the neuromuscular systems to regulate the movement of the center of mass into the horizontal and vertical direction and to control postural alignment both in a static position and during movement [11]. Additionally, this task requires greater hip and knee peak joint moments than other tasks such as ascending stairs [12]. Furthermore, an efficient STS task requires the appropriate amount of the energy to accelerate the center of mass from the sitting position to standing position [13]. Generally, typically developing (TD) children acquire the ability to perform the STS task at approximately 1 year of

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age [14], and it continues to develop as they mature. At approximately 6–7 years old, the kinematics of this task in TD children do not differ from adults [15].

A previous study found that children with SDCP aged 2–6 years old took a longer time to perform the STS task when compared with TD children. The children with SDCP demonstrated an increase in anterior pelvic tilting, and hip flexion angles during the task. Moreover, the maximal power of the hip and knee joint and the maximal extension moments of the knee joint were significantly reduced in these children, and the maximal extension moments of the knee joint showed asymmetry between the legs [16]. Even though, children with SDCP could independently perform the STS, they presented atypical patterns during the STS task [16]. These atypical patterns may increase the energy expenditure in children with SDCP.

Previously, there was no evidence of energy expenditure used during the STS. The direct method of measuring energy expenditure during movement is not appropriate when applied to a non-continuous movement such as STS. Therefore, an analysis of the energy change of moving body segments or mechanical work was used in this study [17,18]. This method showed acceptable sensitivity in analysis of energy expenditure during movement in children with CP [8].

There is a lack of evidence about kinematics, kinetics, and especially energy expenditure during the STS task in children with SDCP. Therefore, the purpose of this study was to investigate the differences in mechanical work, kinematics, and kinetics of the STS task between children with SDCP and TD children aged 7–12 years old. As the STS task involves the performance of both lower extremities, the effects of the dominant and non-dominant legs were also investigated in this study.

2. Material and methods

2.1. Participants

Eleven children with diagnosed SDCP aged from 7 to 12 years and 11 aged and gender-matched TD children were recruited to the study (Table 1). The inclusion criteria for children with SDCP were the following: GMFCS level I or II, able to independently sit to stand without an assistive device, able to follow commands or instructions, and no history of orthopedic surgery within one year or botulinum toxin treatment within 6 months prior to the test. For the TD children, the inclusion criteria were the following: age appropriate standard weight and height based on the national growth chart, and no known neurological or musculoskeletal conditions that could affect the ability to stand up or complete the tasks. Participants from either group were excluded if they could not complete the task testing. Ethical approval was received by the University Ethics Review Committee for Research Involving Human Projects. Prior to the study, written informed consent was obtained from all participants and their guardians.

Table 1
Demographic and anthropometric data of the enrolled children.

Variables	TD children	Children with SDCP
Age (y)	8.50 ± 1.46	8.56 ± 1.64
Gender	8 (72.73)	8 (72.73)
Male	3 (27.27)	3 (27.27)
Female		
GMFCS	–	7 (63.64)
Level I		4 (36.36)
Level II		
Weight (kg)	26.55 ± 4.14	22.40 ± 5.37
Height (cm)	128.52 ± 8.22	118.85 ± 8.24
Thigh length (cm)	28.73 ± 2.15	28.00 ± 2.24
Lower leg length (cm)	35.68 ± 2.95	32.14 ± 2.70

NOTE. Values are mean ± SD, n (%), or as otherwise indicated.

2.2. Procedure

Prior to testing, all participants had demographic data collected, were measured for anthropometric data, the dominant leg was determined, and the markers were attached. The dominant leg was determined by asking participants to kick a ball, pick up a small object from the floor with a foot, and trace a shape on the floor with a foot. The leg that was used to perform the tasks in at least 2 out of 3 tasks was determined as the dominant leg [19]. Next, 29 reflective markers were placed on the participant's body as described by the Helen Hayes marker set model, and two additional markers were placed on the right and the left greater trochanter. The additional markers were used to define the time when the buttock was off the chair. Eight cameras (Raptor E, Motion Analysis Corporation, Santa Rosa, CA) with a sample rate of 120 Hz and two force platforms (Bertec Corp., Columbus, OH) with a sample rate of 1200 Hz were used to collect three-dimensional marker trajectories and the ground reaction force (GRF).

To perform the STS task, the height of the chair was set at 100% of the lower leg length of each participant. In the starting position, the participants sat on the chair with arms crossed across the chest and looking forward. Both feet were kept a shoulder width apart and placed on the force platforms. The lateral malleolus was set to align with the center of the knee joint. The seat depth was set at 30% of thigh length.

Participants were asked to maintain the trunk and head in an upright position and then to perform standing up at their preferred speed, standing steady for 3 s and then sitting down. A few trials of the STS task were allowed to familiarize participants with the study protocol. While performing the STS task, participants could do the task with self-selected patterns, and the foot placement was not constrained except to ensure that each foot was placed on each force platform. Three successful trials of the STS task were collected and used for future analysis.

2.3. Data processing

The regression equations from a study by Jensen [20] was applied to define the segment mass of body segments. These segmental masses and radius of gyration were used to compute the kinematics and kinetics from KinTools RT (Version 2.0, Motion Analysis Corporation, Santa Rosa, CA). The kinematic and kinetic parameters were low-pass filtered with the fourth order Butterworth filter with a cutoff frequency of 6 Hz.

Then, STS phases were categorized into three phases including flexion-momentum, momentum-transfer, and extension phases [21]. First, the flexion-momentum phase (phase I), began with the initiation point of trunk or feet movement (T0) and ended with seat-off (T1). Second, the momentum-transfer phase (phase II), began with seat-off (T1) and ended when the maximum vertical GRF occurred (T2). Third, the extension phase (phase III), began with maximum vertical GRF (T2) and ended with the end of the movement (T3) (Fig. 1). The time from the beginning to the end of the movement was defined as the total movement time. The total movement time and % of the time in each phase were used for future analysis.

Analysis of the energy change of moving body segments, the kinematics, segmental masses, and radius of gyration around the center of mass of each segment were used to calculate the mechanical work [17] by MATLAB. The mechanical work was normalized by body weight for each participant. This value is presented in joules per kilograms (J/kg). The total mechanical work and % of the mechanical work in each phase were used for future analysis.

For the kinematics, the five segments model consisting of trunk, pelvis, thigh, shank, and foot was used in the present study. This model was used to calculate the trunk, trunk-pelvis, pelvis, hip, knee and ankle angles. Trunk and pelvis angles were expressed as the absolute angles of the segments regarding the vertical line of a global reference coordinate system. The trunk-pelvis, hip, knee and ankle angles were expressed as the distal segment relative to the proximal segment. The angle at each time point (T0, T1, T2, and T3) in the sagittal plane during the STS task

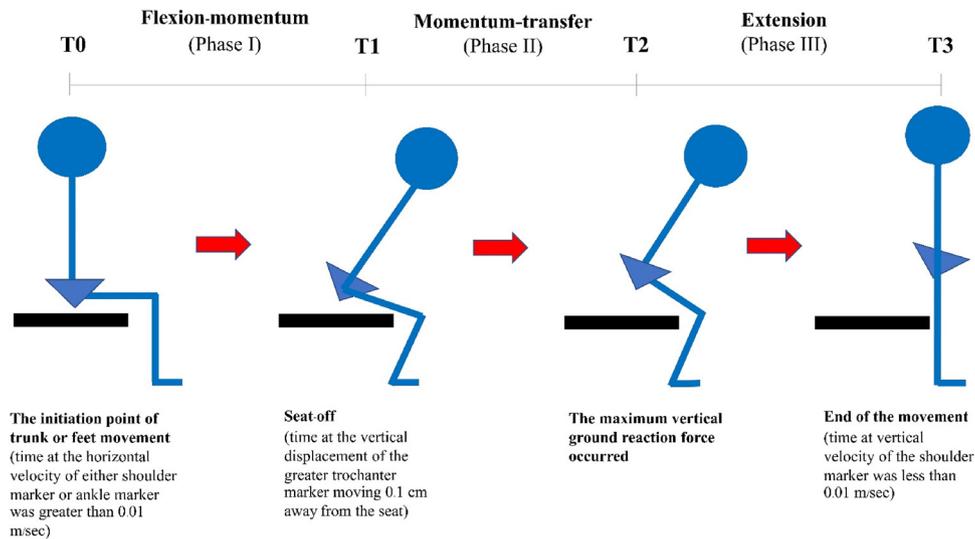


Fig. 1. Sit-to-stand phases.

was calculated for further analysis.

For the kinetics, the inverse dynamics method was used to calculate the maximal internal moments of trunk-pelvis, hip, and knee extension, ankle plantar flexion after seat-off (T1). The peak vertical GRF at seat-off were measured. These variables were normalized by the body weight of each participant.

The kinematics and kinetics were normalized by time with initial movement at 0%, and the end of the movement at 100% of the task and are presented in the graph.

2.4. Statistical analysis

Data analyses were performed with SPSS 22.0 software. The independent *t*-test was used to compare the differences of movement time, mechanical work, the kinematics of the trunk and pelvis, and the kinetics of the trunk-pelvis between the groups. Two-way analysis of variance with post hoc Bonferroni adjustment was used to compare the differences of the kinematics and the kinetics of the lower extremities between sides and groups. For all comparisons, the significance level was set at $p < 0.05$.

3. Results

3.1. Movement time and mechanical work

Children with SDCP presented significantly longer total movement time and a higher % of the time in phase I but a lower % of the time in phase II when compared with TD children. Similar results were found for mechanical work, where the children with SDCP used significantly more total mechanical work and had a higher % of the mechanical work in phase I, whereas they had a lower % of the mechanical work in phase II when compared with TD children (Table 2).

3.2. Kinematics

The mean and SD of the trunk, pelvis, and trunk-pelvis angles at each time point are shown in Table 2. Children with SDCP presented significantly more trunk and trunk-pelvis flexion at T0, T1, T2, and T3 than TD children. For the pelvis angle, children with SDCP only showed a significantly greater posterior pelvic tilt than TD children at T0 (Fig. 2).

Only group main effects for hip, knee, and ankle angles were found in this study. There were significant group main effects for hip angle at T1, T2, and T3. Pairwise comparison showed that children with SDCP

Table 2

Movement time, mechanical work, trunk, pelvis, and trunk-pelvis angle, and trunk moment during sit-to-stand task.

Variables	TD children	Children with SDCP
Movement time		
- Total movement time (s)	1.15 ± 0.22	3.47 ± 1.79*
- Movement time in phase I (%)	47.05 ± 5.85	63.47 ± 15.59*
- Movement time in phase II (%)	16.84 ± 2.13	8.01 ± 4.62*
- Movement time in phase III (%)	35.39 ± 6.43	28.57 ± 13.03
Mechanical work		
- Total mechanical work (J/kg)	2.07 ± 0.16	2.49 ± 0.28*
- Mechanical work in phase I (%)	4.40 ± 1.54	24.83 ± 12.74*
- Mechanical work in phase II (%)	22.03 ± 6.97	8.42 ± 5.19*
- Mechanical work in phase III (%)	73.73 ± 6.91	66.79 ± 14.28
Trunk angle		
- Angle at T0 (°)	0.95 ± 1.59	6.86 ± 5.44*
- Angle at T1 (°)	19.31 ± 6.08	40.64 ± 12.27*
- Angle at T2 (°)	25.52 ± 5.23	47.65 ± 9.45*
- Angle at T3 (°)	5.99 ± 2.70	24.39 ± 13.17*
Pelvis angle		
- Angle at T0 (°)	-6.72 ± 2.47	-14.36 ± 11.11*
- Angle at T1 (°)	9.81 ± 7.33	8.84 ± 11.27
- Angle at T2 (°)	18.82 ± 6.30	15.62 ± 10.09
- Angle at T3 (°)	14.18 ± 6.25	15.23 ± 8.71
Trunk-pelvis angle		
- Angle at T0 (°)	175.11 ± 6.03	160.39 ± 12.18*
- Angle at T1 (°)	176.47 ± 9.92	148.05 ± 8.36*
- Angle at T2 (°)	177.84 ± 8.92	147.77 ± 6.85*
- Angle at T3 (°)	184.01 ± 7.87	171.11 ± 14.23*
Maximum trunk-pelvis extension moment (N.m/kg.)	0.91 ± 0.26	1.45 ± 0.11*

NOTE. Values are mean ± SD, *Significant difference between groups ($p < 0.05$), T0 = starting point, T1 = seat-off, T2 = the maximum vertical ground reaction force occurred, T3 = the end of the movement.

showed greater hip flexion at all time points than TD children. Significant group main effects were found for knee angle at T2, and T3. Children with SDCP showed greater knee flexion at T2 and T3 than TD children. There were significant group main effects for ankle angle at T1, T2, and T3. Pairwise comparison showed that children with SDCP showed lower ankle dorsiflexion at all time points than TD children (Table 3) (Fig. 2).

3.3. Kinetics

The higher maximal trunk-pelvis extension moment was found in children with SDCP as compared to TD children (Table 2). The

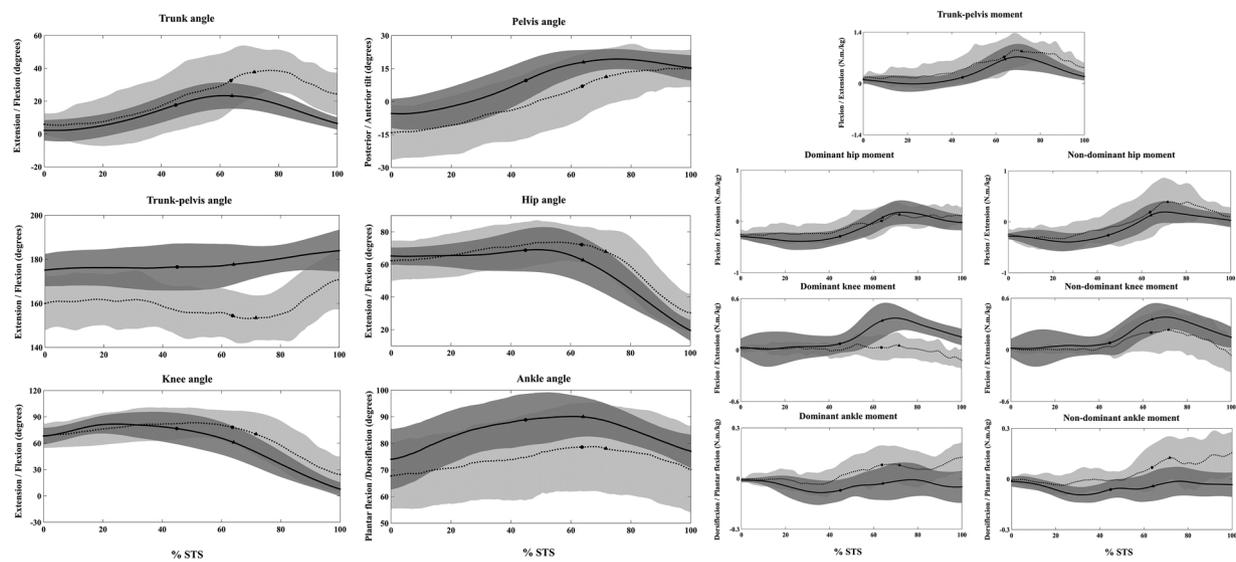


Fig. 2. Sagittal plane trunk, pelvis, trunk-pelvis, hip, knee, ankle motions; and, trunk-pelvis, dominant and non-dominant hip, knee, and ankle moments in TD children (solid line) and children with SDCP (dot line) during sit-to-stand. The symbol (●) represents T1 = seat-off, and (▲) is T2 = the maximum vertical ground reaction force occurred.

Table 3
Hip, knee and ankle angle during the sit-to-stand task.

Variables	TD children	Children with SDCP	F (1,40)	p-value
Hip angle				
- Angle at T0 (°)	64.69 ± 4.07	62.97 ± 11.89	0.39	0.53
- Angle at T1 (°)	72.99 ± 6.88	78.79 ± 10.85	4.27	0.04*
- Angle at T2 (°)	67.51 ± 6.88	75.18 ± 11.84	6.48	0.02*
- Angle at T3 (°)	18.85 ± 5.59	30.29 ± 11.75	16.59	0.01*
Knee angle				
- Angle at T0 (°)	67.70 ± 4.94	68.77 ± 13.23	0.12	0.73
- Angle at T1 (°)	81.64 ± 8.28	84.04 ± 15.79	0.38	0.54
- Angle at T2 (°)	67.15 ± 5.54	77.30 ± 16.13	7.45	0.01*
- Angle at T3 (°)	8.17 ± 5.97	24.34 ± 20.73	11.91	0.01*
Ankle angle				
- Angle at T0 (°)	73.18 ± 4.71	67.66 ± 12.48	3.73	0.06
- Angle at T1 (°)	90.88 ± 7.19	78.47 ± 15.67	11.63	0.01*
- Angle at T2 (°)	92.55 ± 5.51	80.40 ± 16.54	11.58	0.01*
- Angle at T3 (°)	78.02 ± 3.89	70.49 ± 12.32	4.49	0.04*

NOTE. Values are mean ± SD, *Significant difference between groups main effect, T0 = starting point, T1 = seat-off, T2 = the maximum vertical ground reaction force occurred, T3 = the end of the movement.

significant groups × sides interaction was found for maximal hip and knee extension moments, maximal ankle plantar flexion moment, and peak vertical GRF. The mean and SD of all moments and peak vertical GRF for each leg is shown in Table 4. In TD children, maximum moments of all joints were not significantly different between dominant and non-dominant legs. In contrast, these values in children with SDCP

Table 4
Maximal moments of hip and knee extension, ankle plantar flexion and peak vertical ground reaction force.

Variables	TD children		Children with SDCP		Interaction effect	
	Dominant leg	Non-dominant leg	Dominant leg	Non-dominant leg	F (1,40)	p-value
Max. hip extension (N.m/kg.)	0.38 ± 0.17	0.37 ± 0.13	0.36 ± 0.14	0.72 ± 0.22 ^{†‡}	13.07	0.01
Max. knee extension (N.m/kg.)	0.49 ± 0.13	0.51 ± 0.10	0.16 ± 0.09 [‡]	0.41 ± 0.25 [*]	6.54	0.01
Max. ankle plantarflexion (N.m/kg.)	0.12 ± 0.05	0.11 ± 0.06	0.17 ± 0.10	0.27 ± 0.08 ^{†‡}	5.59	0.04
Peak vertical GRF (N/kg.)	5.04 ± 0.62	5.09 ± 0.61	3.49 ± 1.08 [‡]	6.74 ± 1.72 ^{†‡}	23.06	0.01

NOTE. Values are mean ± SD, Max. = maximum moments.

- * Significant difference between dominant and non-dominant leg in children with SDCP group (p < 0.05).
- † Significant difference between non-dominant leg in children with SDCP and TD children groups (p < 0.05).
- ‡ Significant difference between dominant leg in children with SDCP CP and TD children groups (p < 0.05).

were greater for the non-dominant leg. Additionally, the maximal hip extension and ankle plantar flexion moments and peak vertical GRF of the non-dominant leg were greater in children with SDCP than in TD children. Moreover, the maximal knee extension moment and peak vertical GRF of the dominant leg in children with SDCP was lower than in TD children (Fig. 2).

4. Discussion

The present study aimed to study the differences between children with SDCP and TD children aged 7–12 years old in the mechanical work, kinematics, and kinetics as well as the effects of the dominant and non-dominant legs during the STS task. As expected, the results revealed that children with SDCP spent more time completing the STS task than did TD children. This result was in accordance with a previous study done in young children with SDCP [16]. The pathology of the brain leads to an alteration of the neuromuscular control system in children with CP [3–5] resulting in the lower speed and longer time spent performing the movement [22]. Besides the longer movement time, our study found that children with SDCP used more mechanical work than TD children during the STS. The plausible reasons would come from their poor sitting position at the beginning of the movement caused by tightness of hamstring muscle and the consequence of compensatory movement. Children with SDCP sat with slight trunk flexion and posterior pelvic tilting that induced the body vector line to be located more posterior than usual [23]. To compensate for the poor sitting position, children with SDCP showed greater trunk flexion at T2

and T3 compared to TD children.

To explain the characteristics of the STS task, the present study divided the STS task into three phases. Typically, in the flexion-momentum phase, the trunk and pelvis need to move forward, and the feet need to move backward to generate upper-body momentum in the horizontal direction [24,25]. The results of this study revealed that children with SDCP had a higher % of the time and more of the mechanical work in this phase than TD children. Furthermore, at the end of this phase, children with SDCP showed more trunk and hip flexion and less ankle dorsiflexion than TD children. Since children with SDCP usually have tightness of the plantarflexor muscle that limits ankle dorsiflexion, the generation of upper-body momentum could be restricted. Hence, they increased trunk and hip flexion to bring them up at the end of this phase.

For the momentum-transfer phase, this phase involves the transfer of momentum from the upper body to the total body. This phase has been considered as a critical transition phase due to the precise postural control [24,25] and co-contraction of biarticular hamstrings and rectus femoris [25] that are required. Our results found that children with SDCP took less % of the time and used less mechanical work in this phase than TD children. Besides, children with SDCP still had more trunk, hip, and knee flexion and less ankle dorsiflexion compared with TD children at the end of this phase. A previous study showed that during STS, children with spastic CP presented poor postural control [6]. Moreover, these children demonstrated excessive muscle co-contraction during movements such as higher hamstrings and quadriceps co-contraction during walking [26]. Higher muscle co-contraction may alter momentum transferring from the hip to the knee during STS. We assumed that these children compensated for these impairments with increased trunk, hip and knee flexion to place the body vector line between the feet as a new narrower base of support as much as possible.

In the extension phase, the main goal is to move the body vertically to the standing position [24,25]. The results revealed no significant difference in % of the time or mechanical work between the groups. However, at the end of this phase, children with SDCP showed more trunk, hip, knee, and ankle plantar flexion than TD children. Predictably, this standing posture has generally been seen in children with SDCP who have hamstrings and plantarflexor tightness. For the kinetics, the present study found that children with SDCP generated more trunk-pelvis extension moments during STS. This would be another strategy that they used to accomplish the task. Typically, children with spastic CP have difficulty to move their body according to their impairments. Therefore, the greater trunk-pelvis extension moment would be required to lift the body into standing position. In addition, we found an effect of dominant and non-dominant leg during STS, especially in children with SDCP. Asymmetrical weight shifting was revealed at the peak vertical GRF suggesting that children with SDCP took most of their weight on the non-dominant leg, providing more stance stability. Therefore, the moments of the hip, knee and ankle on the non-dominant leg were greater than the dominant leg. Compared to TD children, greater hip extension and plantar flexion moments of the non-dominant leg in children with SDCP were found. This indicated that children with SDCP relied more on hip extensors to bring themselves up into a standing position. In addition, children with SDCP used more plantarflexor to stabilize their standing posture near the end of phase III. A previous study found that the main role of ankle joint moment in the STS task is the maintenance of an upright position [27]. The increased maximum plantar flexion moment in children with SDCP found in this study could be a strategy that was used to maintain the standing position as these children had poor postural control during standing [5].

However, the results of this study were obtained in the children with SDCP in GMFCS level I-II who are able to independently STS. It is important to note that even among these children, STS task still needs to be trained during rehabilitation sessions to improve their quality of life. Additionally, the further studies of the kinematics, kinetics, and especially mechanical work during the STS task in children with SDCP

GMFCS level III would be needed.

In conclusion, to perform the STS task, children with SDCP took a longer time and used more mechanical energy during STS than TD children. In addition, children with SDCP presented more trunk, hip, and knee flexion, and less ankle dorsiflexion during STS. Moreover, all the kinetics including the peak vertical GRF, maximum hip, knee extension, and plantar flexion moments in children with SDCP were asymmetrical between the dominant and non-dominant leg.

Declaration of interest

The authors declare that there is no conflict of interest in relation to this article.

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