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Article *in* Gait & Posture · September 2013

DOI: 10.1016/j.gaitpost.2013.09.009 · Source: PubMed

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Motion of the center of mass in children with spastic hemiplegia: Balance, energy transfer, and work performed by the affected leg vs. the unaffected leg

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ARTICLE INFO

Article history:
Received 1 February 2013
Received in revised form 13 September 2013
Accepted 15 September 2013

Keywords:
Gait
Center of mass
Hemiplegia
Balance
Work

ABSTRACT

Asymmetry between limbs in people with spastic hemiplegic cerebral palsy (HEMI) adversely affects limb coordination and energy generation and consumption. This study compared how the affected leg and the unaffected leg of children with HEMI would differ based on which leg trails. Full-body gait analysis data and force-plate data were analyzed for 31 children (11.9 ± 3.8 years) with HEMI and 23 children (11.1 ± 3.1 years) with typical development (TD). Results showed that peak posterior center of mass-center of pressure (COM-COP) inclination angles of HEMI were smaller than TD when the affected leg trailed but not when the unaffected leg trailed. HEMI showed greater peak medial COM-COP inclination angles and wider step width than TD, no matter which leg trailed. More importantly, when the affected leg of HEMI trailed, it did not perform enough positive work during double support to propel COM motion. Consequently, the unaffected leg had to perform additional positive work during the early portion of single support, which costs more energy. When the unaffected leg trailed, the affected leg performed more negative work during double support; therefore, more positive work was still needed during early single support, but energy efficiency was closer to that of TD. Energy recovery factor was lower when the affected leg trailed than when the unaffected leg trailed; both were lower than TD. These findings suggest that the trailing leg plays a significant role in propelling COM motion during double support, and the 'unaffected' side of HEMI may not be completely unaffected. It is important to strengthen both legs.

1. Introduction

Traditionally gait analysis focuses on joint kinematics and kinetics. Assessment of motion of whole-body center of mass (COM) is not included in most clinical gait studies. Parameters of COM excursion have been shown to be sensitive measurements in distinguishing elderly individuals with balance problems from healthy elderly adults [1] and assessing balance during gait of children with cerebral palsy [2] (CP). COM motion has also been shown to reflect efficiency of energy transfer between potential and kinetic energies during gait in children with spastic diplegia [3]. In addition, it has been shown that the trailing leg of children with spastic diplegia performs a diminished amount of positive work on COM during double support. Thus, the leading leg needs to perform more positive work during the early portion of single support [4].

COM parameters can serve as a tool for quantitative assessment of overall gait quality reflected in balance and mechanical work. Because COM parameters are a summary of all segmental abnormalities, they can aid in objectively evaluating severity of gait pathology and intervention outcome. Patients with CP have varying impairments of the locomotor system including balance, motor control, and strength. COM parameters may provide new insights to explain the differing functional abilities in an apparent similar population group, e.g. hemiplegia, and the varying clinical outcomes to interventions.

CP is caused by an injury to the immature brain [5]. Spastic hemiplegic CP (HEMI) is an involvement of one side of the body with relative sparing of the contralateral limbs [5]. Asymmetry between limbs in HEMI can adversely affect limb coordination during double support and the early portion of single support. Better understanding of the contributions to this potential inefficiency will provide more information on the role of each leg in balance, energy generation and consumption.

The purpose of the study was to compare how the affected leg and unaffected leg of children with HEMI would differ based on which leg trails. We hypothesized that: (1) HEMI would demonstrate

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http://dx.doi.org/10.1016/j.gaitpost.2013.09.009

greater COM movement relative to center of pressure (COP) in the sagittal and coronal planes than children with typical development (TD); (2) The trailing leg would perform less positive work on COM during double support when the affected leg of HEMI trails than when the unaffected leg trails.

2. Methods

2.1. Subjects and procedures

Thirty-one subjects with HEMI were retrospectively identified from patients who had clinical gait analysis in the motion analysis lab. They include 19 male and 12 female; 12 left hemiplegia and 19 right hemiplegia; age = 11.9 ± 3.8 years, mass = 43.3 ± 14.3 kg, height = 1.481 ± 0.17 m, affected leg length = 0.771 ± 0.103 m, unaffected leg length = 0.776 ± 0.103 m. All were independent community ambulators with Gross Motor Function Classification System levels I (26 subjects) and II (5 subjects). None had any orthopedic surgery within one year before gait analysis. Eight subjects had osteotomies or muscle/tendon lengthenings at least one year before gait analysis. All had gait analysis with full-body marker set and data from two consecutive force plates when walking barefoot. All had two trials with affected leg trailing and two trials with unaffected leg trailing during double support. Data from an age matched group of 23 children with TD (14 male and 9 female, age = 11.1 ± 3.1 years, mass = 39.7 ± 17.6 kg, height = 1.467 ± 0.203 m, left leg length = 0.772 ± 0.116 m, right leg length = 0.774 ± 0.116 m) served as a comparison. There was not a significant difference in age between the two groups. The study was approved by Institution Review Board.

A full-body marker set of 29 reflective markers was placed on bony landmarks, according to the upper extremity [6] and lower extremity [7] models. Subjects walked at a self-selected speed along a walkway. Three-dimensional kinematic data were collected at 120 Hz using an 8-camera Vicon system (Oxford Metrics Group). Ground reaction forces (GRF) was collected at 1080 Hz using two strain-gauge force plates (AMTI Inc.).

2.2. Data analysis

Based on joint centers calculated using upper extremity [6] and lower extremity [7] models, 13 body segments (trunk–head–neck, pelvis, upper arms, forearms, hands, thighs, shanks and feet) were defined. A biomechanical model [8] was used to calculate COM from kinematic data. In this model, regression equations [9] were used to define segment mass and COM position for children 15 years of age or younger; Dempster's anthropometric data [10] were used for subjects over the age of 15 years. Position of full body COM was calculated as weighed sum of all body segments. This model has been validated by comparing COM calculated from force plate data and from kinematic data; it has been used to calculate COM in children with CP [3]. Other studies [11,12] also showed that COM calculated from force plate data agrees with COM calculated from kinematic data.

COP position was calculated using GRF and moments measured using the two force plates. During double support, a resultant COP was calculated from COP and vertical GRF of each foot. COP data was synchronized with kinematic data and had the same sampling rate.

Medial–lateral and anterior–posterior COM-COP inclination angles were formed by the intersection of the line connecting COP and COM with a vertical line through the COP [1] (Fig. 1a). Peak anterior, posterior, and medial COM-COP inclination angles were calculated.

External mechanical power performed by each leg on COM was calculated from the dot products of GRF exerted on the leg and velocity of COM [13]. This was the power delivered to COM by all muscles that contributed to GRF. External mechanical work was calculated by integrating the power curve over the time domain of double support and over the time domain of early portion of single support, respectively [4]; the work was then normalized by body mass, leg length and gravity [14].

The energy recovery factor (R) was calculated to represent percentage of mechanical energy recovered from exchange between kinetic and potential energies in COM motion [3]:

$$R = \frac{Wne - Wext}{Wne}$$

where $Wext = \sum_{i=1}^{N} |\Delta PE + \Delta KE|$ and $Wne = \sum_{i=1}^{N} |\Delta PE| + |\Delta KE|$.

PE and KE are potential and kinetic energies of COM calculated based on COM vertical location relative to its mean position and magnitude of COM velocity [3]. R has a value between 0% and 100%. The higher the percentage, the more efficient the energy exchange.

Temporal-distance gait parameters were calculated because COM motion has been shown to be affected by gait velocity [16,17].

Balance and energy variables were calculated for the period between the heel-strike of the leading leg to the heel-strike of the trailing leg. Temporal-distance gait parameters were calculated for the gait cycle from heel strike of the leading leg to the next heel strike of the same leg.

All COM parameters were calculated using a customized Matlab (MathWorks Inc.) program.

2.3. Statistical analysis

Two-tailed two-sample equal variance t-test was used to detect significant differences between HEMI and TD. Two-tailed paired t-test was used to detect differences between the affected leg and unaffected leg when it was the trailing leg in HEMI. Bonferroni correction was applied to counteract the increased likelihood of type I error of multiple comparisons. Significance level for each family of tests was set as 0.05. The p value of each t-test was adjusted by multiplying the number of tests in the family. The reported p value was the adjusted value.

3. Results

There were no significant differences in walking speed, cadence, stride length or step length between the groups (Table 1). Trailing

Table 1
Gait temporal-distance measurements for typically developing children (TD) and children with spastic hemiplegic cerebral palsy (HEMI). For the HEMI, the gait parameters were of the leading leg.

	Typically developing children ($n = 23$)	Children with spastic hemiplegia ($n = 31$)		
		When unaffected leg trails	When affected leg trails	Difference between legs
Gait velocity (m/s)	1.062 ± 0.182	1.051 ± 0.198	1.041 ± 0.177	
Cadence (steps/min)	116 ± 18	119 ± 15	118 ± 16	
Stride length/leg length	1.443 ± 0.161	1.391 ± 0.191	1.380 ± 0.173	
Step length/leg length	0.721 ± 0.084	0.686 ± 0.115	0.685 ± 0.098	
Step width/leg length	0.096 ± 0.049	0.178 ± 0.073*	0.152 ± 0.069*	

* Bonferroni adjusted $p < 0.05$ when comparing between HEMI and TD, or when comparing between the unaffected leg and the affected leg acting as trailing leg in HEMI.

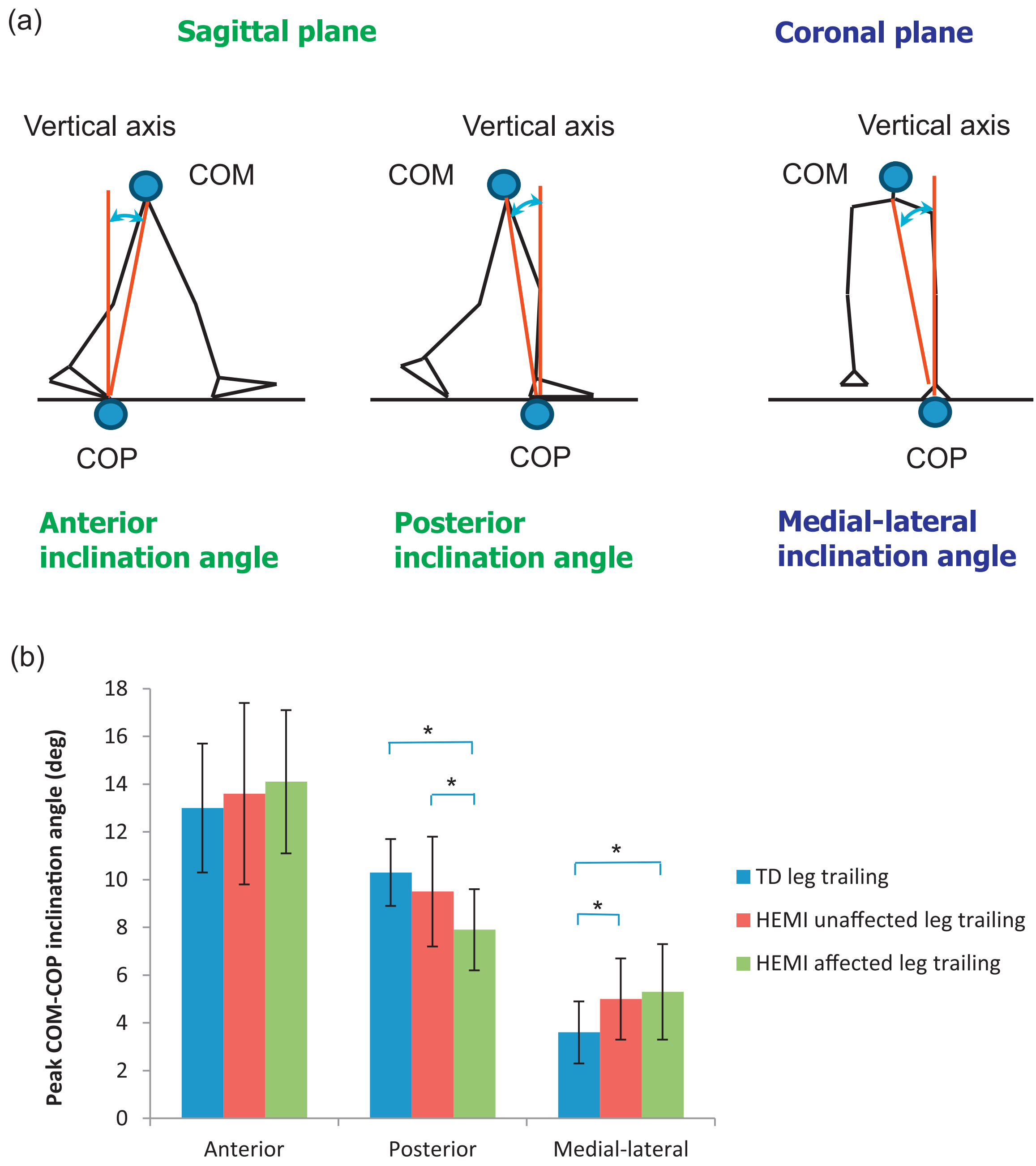

Fig. 1. (a) Illustration of COM-COP inclination angles in the sagittal and coronal planes [1]. (b) Peak COM-COP inclination angles. * Indicates Bonferroni adjusted $p < 0.05$ when comparing between HEMI and TD, or when comparing between the unaffected leg and the affected leg acting as trailing leg in HEMI.

by the affected leg or unaffected leg did not make significant differences in these gait parameters either. The only difference in gait temporal-distance parameters was shown in step width, which was significantly greater in HEMI than in TD.

Significant differences were found in the peak medial–lateral COM-COP inclination angles and the peak posterior COM-COP inclination angles between HEMI and TD (Fig. 1b). Peak posterior COM-COP inclination angles of HEMI were significantly smaller than those of TD when affected leg trailed but not when unaffected leg trailed. HEMI had significantly greater peak medial–lateral COM-COP inclination angles than TD no matter which leg trailed. Peak medial–lateral COM-COP inclination angle and the step width normalized by leg length were strongly correlated for TD ($r = 0.825$, $df = 21$, $p < 0.001$) but not for HEMI ($r = 0.165$ when unaffected leg trailed; $r = 0.020$ when affected leg trailed).

Fig. 2a shows an example of the limb power curves during stance for a child with TD. During double support, the leading (weight-accepting) leg performs negative work on COM as it absorbs energy and decelerates the forward motion of COM. Meanwhile, the trailing (push-off) leg performs positive work so that its energy increases and COM forward motion is maintained. Despite inefficiencies inferred by the concurrent events, these events are essential to safe and smooth walking pattern. Fig. 2b and c shows an example of a child with HEMI. When the affected leg trails, it does not perform enough positive work to balance the negative work performed by the leading leg. Consequently, additional positive work must be performed on COM during single support to maintain COM motion.

Mechanical work and energy recovery factor are summarized for the groups in Table 2. The major significant difference between

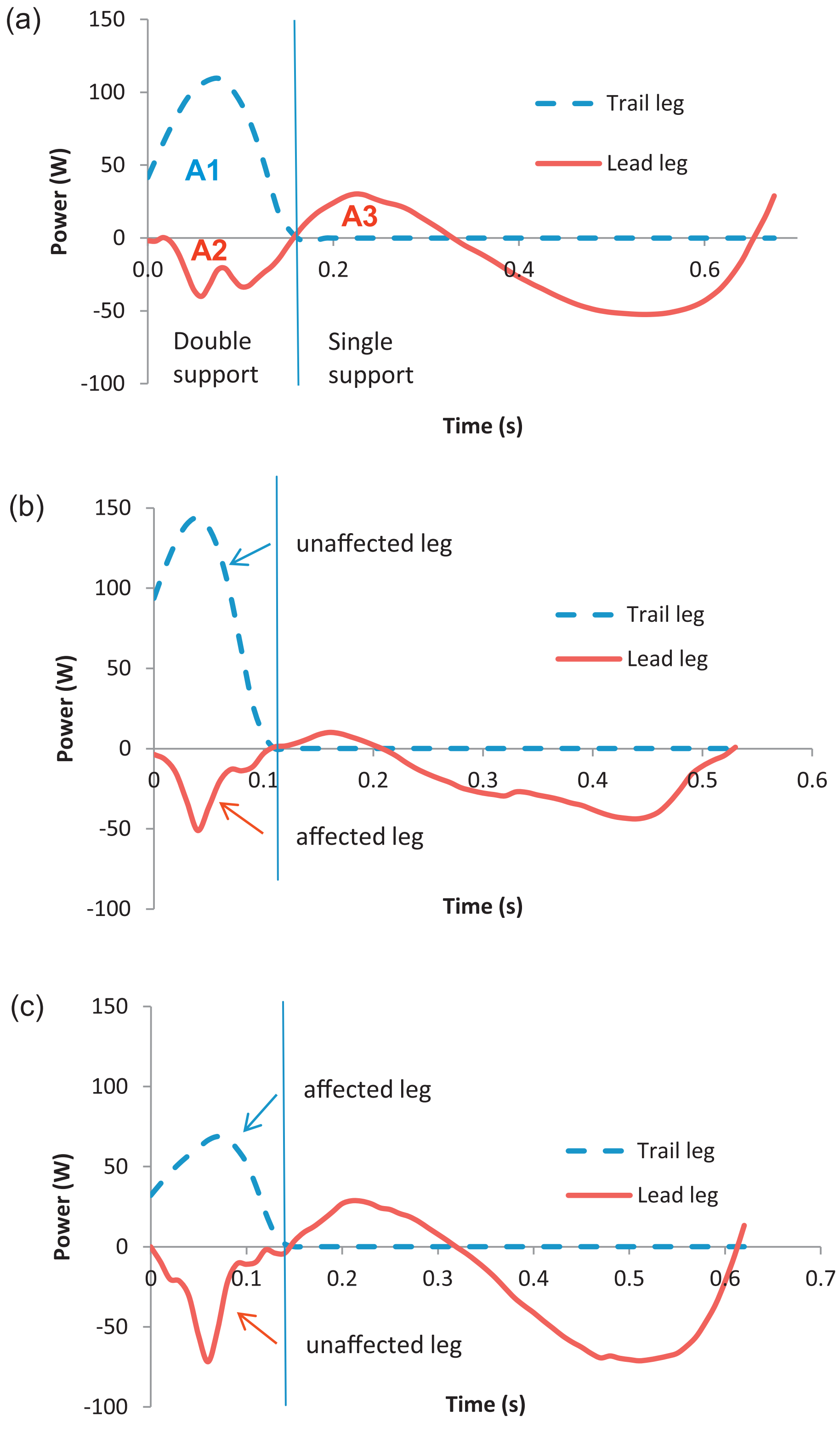

Fig. 2. Limb power curves during stance for: (a) A child with normal development. Work is calculated as the integral of the power curve over the time domain. A1 (area 1) is positive work done by the trailing leg during double support. A2 is negative work done by the leading leg during double support. A3 is positive work by the leading leg during single support. (b) A child with HEMI when the unaffected leg trails. (c) A child with HEMI when the affected leg trails.

the affected leg and unaffected leg of HEMI in performing mechanical work was shown in double support, and it depended on which leg trailed. When the unaffected leg trailed, HEMI performed similar amount of positive work by the trailing leg compared with TD (HEMI: 0.022 ± 0.011, TD: 0.020 ± 0.004). When the affected leg trailed, HEMI performed significantly less positive work by the trailing leg compared with TD (HEMI: 0.015 ± 0.007, TD: 0.020 ± 0.004, $p < 0.05$). The affected leg being the trailing leg performed significantly less positive work than the unaffected leg being the trailing leg during double support (0.015 ± 0.007 vs. 0.022 ± 0.011, $p < 0.005$). The amount of negative work performed by leading leg of HEMI was not significantly different from TD

Table 2
Mechanical work.

		Typically developing children ($n = 23$)	Children with spastic hemiplegia ($n = 31$)		
			When unaffected leg trails	When affected leg trails	Difference between legs
Normalized work during double support	Trailing leg	0.020 ± 0.004	0.022 ± 0.011	0.015 ± 0.007*	*
	Leading leg	−0.012 ± 0.007	−0.019 ± 0.014	−0.017 ± 0.017	
Normalized positive work of leading leg during single support		0.007 ± 0.004	0.017 ± 0.019	0.021 ± 0.022*	

* Bonferroni adjusted $p < 0.05$ when comparing between HEMI and TD, or when comparing between the unaffected leg and the affected leg acting as trailing leg in HEMI.

(−0.012 ± 0.007) no matter which leg trailed (unaffected leg: −0.019 ± 0.014, affected leg: −0.017 ± 0.017), although there was a trend of the leading leg of HEMI performing more negative work than TD during double support.

Work performed in the fore-aft, medio-lateral, and vertical directions during double support was also analyzed to gain more insight into the function of muscles in providing vertical support or forward propulsion. Fig. 3 shows that the primary contribution to total work was in the fore-aft direction (forward propulsion), followed by the vertical direction (vertical support). The trailing leg performed more positive work in the fore-aft direction when unaffected leg trailed than when affected leg trailed (0.025 ± 0.009 vs. 0.018 ± 0.008, $p < 0.005$), although neither was significantly different from TD (0.02 ± 0.003). Compared to TD, the leading leg of HEMI performed more negative work in the fore-aft direction when unaffected leg trailed (−0.026 ± 0.014 vs. −0.017 ± 0.016, $p < 0.05$).

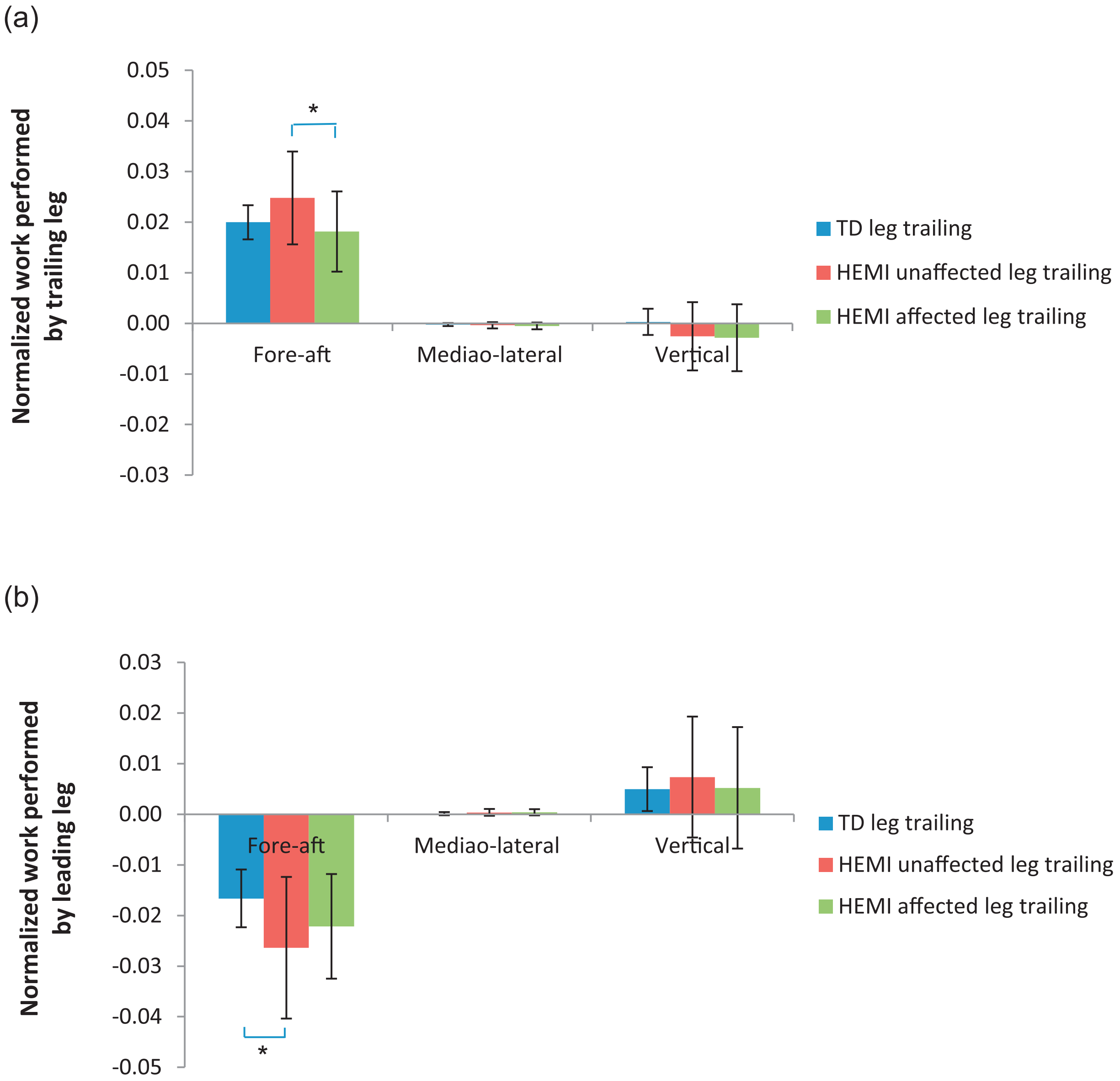

Fig. 3. Normalized work performed in the fore-aft, medio-lateral, and vertical directions during the double support phase. (a) By the trailing leg; (b) by the leading leg. * Indicates Bonferroni adjusted $p < 0.05$ when comparing between HEMI and TD, or when comparing between the unaffected leg and affected leg acting as trailing leg in HEMI.

Negative work in the fore-aft direction performed by the leading leg when affected leg trailed (-0.022 ± 0.01) was not significantly different from TD (-0.017 ± 0.016). Work in the vertical direction did not show significant differences. These results showed that differences in work performed by TD/unaffected/affected legs during double support were primarily in the fore-aft direction.

Mechanics of the legs during double support affected the positive work needed in the early portion of single support (Table 2). When the unaffected leg trailed, the positive work during single support was not significantly different between HEMI (0.017 ± 0.019) and TD (0.007 ± 0.004), although there was a trend of HEMI performing more positive work than TD during single support. When the affected leg trailed, significantly more positive work during single support was needed for HEMI (HEMI: 0.021 ± 0.022, TD: 0.007 ± 0.004, $p < 0.005$) because not enough positive work was performed by the trailing leg during double support.

The energy recovery factor was significantly lower ($p < 0.05$) when affected leg trailed ($41.7 \pm 14.1\%$) than when unaffected leg trailed ($47.6 \pm 16.9\%$), though both were lower ($p < 0.005$) than TD ($63.7 \pm 11.7\%$). This indicates that energy transfer was less efficient in HEMI than TD, and it was worse when affected leg trailed than when unaffected leg trailed.

4. Discussion

The results of this study supported our hypothesis that HEMI demonstrated greater COM-COP inclination angles in the sagittal and coronal planes. The results also supported our hypothesis that when the affected leg of HEMI trailed (pushed-off) during double support, it did not perform enough positive work to propel COM motion. Consequently, additional positive work must be done by the unaffected leg during the early portion of single support, which costs more energy. When the unaffected leg trailed, the affected leg performed more negative work during double support. Therefore, more positive work was still needed during the early portion of single support. However, energy efficiency was closer to that of TD.

Gait velocity was similar between the groups in this study. It might be due to three reasons: (1) The groups were similar in age. (2) To be included in this retrospective study, the trials needed to have data from two consecutive force plates. The constraints introduced by the dimension and setup of the force plates tend to favor trials of similar gait velocity. (3) The HEMI subjects who had two consecutive force plate strikes might be mildly involved because it is harder for the more involved subjects to have clean force data from two consecutive plates due to their reduced stride length. COM motion has been shown to be affected by gait velocity [16,17]. The similarity in gait velocity provides more validity in comparing COM variables between the groups and avoids taking velocity effect into account.

Despite similar gait velocity of HEMI and TD, step widths of HEMI were significantly wider than those of TD. Furthermore, peak medial COM-COP inclination angles and normalized step width were strongly correlated for TD but not for HEMI no matter which leg trailed. Step width is associated with both lateral balance and metabolic cost. Metabolic cost has been reported [18] to be lowest when step width is 0.12 times of the leg length, and the mechanical work that is performed to redirect the COM during the transition between steps increases with the square of step width. It has also been shown [19] that frontal plane trunk kinematics during swing phase explains a significant portion of variance in the subsequent step widths. The mismatches between frontal plane trunk COM kinematics (as indicated by COM-COP inclination angle in this study) and subsequent step widths in HEMI may increase the probability of a loss of stability.

Biomechanical variables related to energetics contain important information about pathological gait [10]. Mechanical work calculations are essential to assessment of efficiency. The trailing leg of children with spastic diplegia performs a diminished amount of positive work on COM during double support [4]. Thus, the leading leg needs to perform greater amount of positive work during the early portion of single support [4]. Hemiparetic patients showed differences in kinetic and kinematic parameters with respect to the starting limb [20]. COP and COM motion and the symmetry parameters are related to a higher degree of uncertainty when starting with the unaffected leg because of weakness of the supporting limb in hemiparetic subjects [20]. An investigation on the effects of age on COM motion [21] showed that older adults did less positive work on COM during push-off but then performed more positive work on COM during midstance. Older adults use the leading leg to compensate for reduced vertical support and work done by the trailing leg. The higher energy cost of walking in children with HEMI was attributed to poor patterns of exchange between the potential and kinetic energy of the body segments and to the low levels of kinetic energy that precluded the exchange [22]. Increased energy cost of walking was related to an increase in mechanical work done by the muscles rather than a decrease in efficiency of work production by muscles in hemiparetic patients [23] and children with hemiplegic CP [24]. The results of this study on mechanical work on COM are consistent with previous studies in children with spastic diplegia [3,4]. Furthermore, this is the first study to demonstrate that mechanical work in double support affects the positive work needs to be done in single support, and which leg trails makes a significant difference in HEMI.

Gait deviation index of the unaffected side for type I hemiplegia was reported to be one full standard deviation away from the norms [15], and 30% of the hemiplegic children showed impairment of the unaffected hand [25]. The current study showed the unaffected leg still demonstrates significant differences from norms in energy recovery factor; it suggested that the unaffected leg of HEMI might not be completely ‘unaffected’.

To compensate for the affected leg, HEMI relied more on the unaffected leg to maintain balance and generate power. This could possibly fatigue or strain the unaffected leg. The findings of this study support the recommendation [26] that rehabilitation programs should include strengthening of the unaffected leg to avoid fatigue or injury.

The above findings suggest the significant role of the trailing leg during double support when planning intervention. Muscle weakness is a major impairment in subjects with CP, and many treatments result in weakening of muscles. It is important to preserve power generation when making treatment plans. The mean power generation from the ankle has been reported [27] to be 7.6 w/kg on the hemiplegic side and 15.9 w/kg on the unaffected side of HEMI. It was also demonstrated [28] that increases in ankle strength could improve gait and function in people with CP. The current study shows that the affected leg of HEMI did not perform enough positive work to propel COM motion when it trailed, providing further evidence that procedures that weaken the calf musculature should be undertaken with caution. In addition, it is functionally important to strengthen both legs because the ‘unaffected’ leg might not be completely unaffected. Determination of a specific strengthening program could be made after clinical assessment of the patient with emphasis on gluteus maximus, gluteus medius, vasti, hamstrings, gastrocnemius, and soleus which have been identified to be the primary contributors to vertical support and forward progression in a previous study [29].

The application of COM parameters in clinical gait analysis provides quantitative assessment of balance control, whole body coordination, and energy efficiency. These measurements could be more relevant to the patient’s gait abnormality and also very useful as an assessment tool. This additional measure of impairment provides a better understanding of the underlying deficits that are present. This will lead to a more objective understanding of the potential improvements with interventions.

Acknowledgements

The authors would like to thank Dr. Frank Buczek, Dr. Dustin Bruening, and Kevin Cooney for assistance with this project.

Conflict of interest: There are no conflicts of interest for this investigation.

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