ACTA ORTHOPAEDICA et TRAUMATOLOGICA TURCICA

Acta Orthop Traumatol Turc 2009;43(2):156-164
doi:10.3944/AOTT.2009.156

Upper extremity kinetics and energy expenditure during walker-assisted gait in children with cerebral palsy

Beyin felçli çocuklarda yürüteç kullanımı sırasında üst ekstremite kinetikleri ve enerji tüketimi

Katherine A. KONOP,[1,2] Kelly M. B. STRIFLING,[1,2] Mei WANG,[2,5] Kevin CAO,[2] Daniel EASTWOOD,[3] Scott JACKSON,[3] Jeffrey ACKMAN,[4] Haluk ALTIOK,[4] Jeffrey SCHWAB,[5] Gerald F. HARRIS[1,2,4,5]

[1]Department of Biomedical Engineering and [2]Orthopaedic and Rehabilitation Engineering Center, Marquette University, Milwaukee, WI; Departments of [3]Biostatistics and [5]Orthopedic Surgery, Medical College of Wisconsin, Milwaukee, WI; [4]Shriners Hospital for Children, Chicago, IL;

Objectives: We evaluated the relationships between upper extremity (UE) kinetics and the energy expenditure index during anterior and posterior walker-assisted gait in children with spastic diplegic cerebral palsy (CP).

Methods: Ten children (3 boys, 7 girls; mean age 12.1 years; range 8 to 18 years) with spastic diplegic CP, who ambulated with a walker underwent gait analyses that included UE kinematics and kinetics. Upper extremity kinetics were obtained using instrumented walker handles. Energy expenditure index was obtained using the heart rate method (EEI_{HR}) by subtracting resting heart rate from walking heart rate, and dividing by the walking speed. Correlations were sought between the kinetic variables and the EEI_{HR} and temporal and stride parameters.

Results: In general, anterior walker use was associated with a higher EEI_{HR}. Several kinetic variables correlated well with temporal and stride parameters, as well as the EEI_{HR}. All of the significant correlations (r>0.80; p<0.005) occurred during anterior walker use and involved joint reaction forces (JRF) rather than moments. Some variables showed multiple strong correlations during anterior walker use, including the medial JRF in the wrist, the posterior JRF in the elbow, and the inferior and superior JRFs in the shoulder.

Conclusion: The observed correlations may indicate a relationship between the force used to advance the body forward within the walker frame and an increased EEI_{HR}. More work is needed to refine the correlations, and to explore relationships with other variables, including the joint kinematics.

Key words: Biomechanics; cerebral palsy; child; energy metabolism; gait disorders, neurologic; heart rate; kinetics; muscle spasticity; upper extremity; walkers; walking/physiology.

Amaç: Çalışmada, spastik diplejik beyin felçli çocuklarda, ön ve arka yürüteç kullanımı sırasında üst ekstremite (ÜE) kinetik verileri ile enerji tüketim indeksi arasındaki ilişkiler araştırıldı.

Çalışma planı: Yürüteçle yürüyebilen, spastik diplejik beyin felçli 10 çocukta (3 erkek, 7 kız; ort. yaş 12.1; dağılım 8-18) ÜE kinematiği ve kinetiği ile ilgili yürüme analizleri yapıldı. Üst ekstremite kinetiği ile ilgili veriler yürüteç tutacaklarına yerleştirilen donanım ile elde edildi. Enerji tüketim indeksi, kalp hızı yöntemiyle ($ETİ_{KH}$), yürüme sırasındaki kalp hızından dinlenme anındaki kalp hızının çıkarılması ve sonucun yürüyüş hızına bölünmesiyle hesaplandı. Kinetik değişkenler ile $ETİ_{KH}$ ve yürümenin zamansal ve adım parametreleri arasındaki korelasyonlar araştırıldı.

Sonuçlar: Genel olarak, ön yürüteç kullanmada $ETİ_{KH}$'nin daha yüksek olduğu görüldü. Birçok kinetik değişken, yürümenin zamansal ve adım parametreleri ve $ETİ_{KH}$ ile korelasyon gösterdi. Anlamlı korelasyonların tümü (r>0.80; p<0.005) ön yürüteç kullanımı sırasında görüldü ve eklem reaksiyon momentlerinden çok kuvvetleri ile ilgiliydi. Bazı kinetik değişkenlerin ön yürüteç kullanımı sırasında güçlü ve çoklu korelasyon gösterdiği gözlendi: Bunlar el bileği medial eklem reaksiyon kuvveti (ERK), dirsek eklemi posterior ERK ve omuz eklemi inferior ve superior ERK'leri idi.

Çıkarımlar: Gözlenen korelasyonlar, yürüteç içinde öne hareket için harcanan güç ile artmış $ETİ_{KH}$ arasında ilişki olabileceğini göstermektedir. Bu ilişkinin daha açık hale getirilmesi ve eklem kinematiği de dahil diğer değişkenlerle ilişkilerin araştırılması için yeni çalışmalara ihtiyaç vardır.

Anahtar sözcükler: Biyomekanik; beyin felci; çocuk; enerji metabolizması; yürüme bozukluğu, nörolojik; kalp hızı; kinetik; kas spastisitesi; üst ekstremite; yürüteç; yürüme/fizyoloji.

Correspondence / *Yazışma adresi:* Gerald Harris, MD. Department of Orthopedic Surgery, Medical College of Wisconsin, P.O. Box 26099, Milwaukee, WI 53226, USA. Tel: +1 414 288 0698 e-mail: gerald.harris@marquette.edu

Submitted / *Başvuru tarihi:* 26.09.2008 **Accepted / *Kabul tarihi:*** 08.03.2009

Cerebral palsy (CP) is a neurological disorder which affects 3-4 babies per 1000 live births in the United States.[1] Many cases of CP are characterized as spastic (velocity-dependent increase in muscle tone) and diplegic (affects the lower limbs more severely than the uppers). Many children with this type of CP use mobility aids, including anterior and posterior walkers (Fig. 1), for stability.

It is important to study the upper extremity (UE) kinetics of children with CP during walker use because of the increased magnitude and repetition of loads on the arms.[2-4] Shoulder injury or arthritis later in life has been linked to the prolonged use of walking aids and wheelchairs.[5,6] Studies examining UE kinetics during walking aid use are rare, and many focus on canes and Lofstrand crutches.[4,7] Preliminary kinetic analyses on walker loading has been completed;[6,8-11] however, these studies are mainly concerned with overall walker forces via use of strain gages on the walker legs. A bilateral UE kinetic analysis could not be completed using this type of data. Furthermore, only very preliminary work has been done on bilateral UE kinetics by our group.[12]

It is well-documented that children with CP use more energy when walking than unimpaired children.[13-17] However, reasons for the increased energy use remain unclear. It is hypothesized that either kinematic inefficiency or muscle co-contraction leads to this increase. Van den Hecke et al.[17] determined that an increase in mechanical work due to segmental impairments leads to increased energy cost during walking. The relationship between UE loading and energy expenditure during ambulation with walkers has not been investigated.

Energy expenditure during gait can be determined by several methods, including energy expenditure index using heart rate (EEI_{HR})[13,14,18-20] and oxygen consumption (VO_2).[13,17,18,21-23] While oxygen consumption is considered the gold standard in measuring energy use, EEI_{HR} is simpler to perform and does not require the use of burdensome equipment. The oxygen consumption method requires the use of a face mask and a cart or pack that is used to determine the volume of oxygen consumed and carbon dioxide produced. Rose et al.[15] determined that EEI_{HR} is an appropriate method to estimate energy expenditure in children with CP during gait. This assertion has been challenged recently. Keefer et al.[18] compared the measures in children with hemiplegic CP, and found low correlation values; they recommended using caution when using the EEI_{HR} method. Norman et al.[13] studied the same issue in children with spastic diplegic CP walking at a self-selected speed and found that EEI_{HR} served as a reasonable indicator to assess energy use in this population.

Several studies examined the energy expenditure during gait with anterior and posterior walkers in children with CP. Using oxygen consumption, Park et al.[24] found that the posterior walker was associated with significantly lower energy expenditure than the anterior walker, but Mattsson and Andersson[25] found no difference between the walker types. Strifling et al.[26] also found no difference in EEI_{HR} between the two walker types.

The current study explored the relationship between three-dimensional UE kinetics and EEI_{HR} in children with CP using anterior and posterior walkers.

Patients and methods

Ten children (3 boys, 7 girls; mean age 12.1 years; range 8 to 18 years) with spastic diplegic CP were analyzed. Participation criteria required that the subjects routinely used a walker for at least a one-month period, and presented with an Ashworth score of 2 or less (slight increase in tone) in the elbow joint. Those who had received botulinum toxin type A treatment anywhere in the body within six months, or undergone prior surgery within one year of starting the study were excluded.

Demographic characteristics of the patients are shown in Table 1. All subjects were using posterior walkers before the study. Appropriate institutional review board approval and parental consent were obtained before beginning the study.

Data collection

Motion data were recorded by placing reflective surface markers on the UEs and lower extremities.

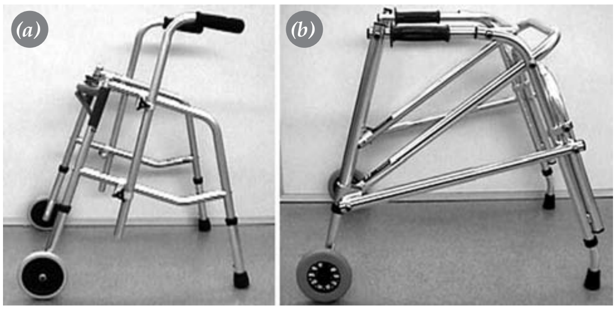

Fig. 1. Walker types: **(a)** anterior and **(b)** posterior walkers.

Table 1. Demographic and clinical characteristics of the patients

Patient	Age+	Sex	Height (m)	Weight (kg)	Dominance	Ashworth+& Left	Ashworth+& Right	GMFCS*
1	18	M	1.4	38.7	Right	2	2	3
2	12	F	1.3	32.2	Left	1	2	3
3	13	F	1.4	42.2	Right	1	1	3
4	13	F	1.3	55.6	Left	1	1	3
5	8	F	1.1	18.8	Left	1	1	3
6	11	F	1.3	25.2	Right	2	2	3
7	9	M	1.2	21.8	Right	2	2	3
8	18	F	1.4	50.8	Right	1	1	4
9	9	F	1.2	27.4	Right	2	2	3
10	10	M	1.3	43.2	Left	1	1	3
Mean	12.1		1.3	35.6				

GMFCS: Gross Motor Function Classification System for Cerebral Palsy; +Data collected at subject's first visit. *A GMFCS score of 3 means that the child mainly walks with an assistive device and a score of 4 means that the child uses a walker, but depends more on wheeled mobility. &An Ashworth score of 1 indicates no increase in muscle tone and a score of 2 indicates a slight increase in tone.

The marker set was previously described by our group.[26]

Three sizes of walkers were available to accommodate different patient heights (anterior walkers: Sunrise Medical, Model 7783, 7781, 7780, Longmont, CO; posterior walkers: Kaye Products, Inc., Model W2B-W4B, Hillsborough, NC). The walkers were adjusted so that the handle reached the subjects' ulnar styloid process when standing with arms at their side. Motion data were collected with the subject using his/her usual walker type (posterior). It is well-known that the spastic effects of CP are variable between subjects;[27] therefore, at least five walking trials were collected to ensure that three acceptable gait cycles were obtained. The trials were conducted at a self-selected speed and walking style. The motion data were collected at 60 Hz using a 12-camera Vicon motion analysis system (Oxford Metrics, Oxford, UK).

Kinetic data were collected at 1500 Hz using two specially designed walker handles (AMTI, Watertown, MA), each instrumented with a 6-axis strain gage-based load cell to measure three forces and three moments acting at the hand. After an acclimation period of at least 30 days, the same testing procedure was performed using the alternate walker type (anterior walker). In a survey conducted at the completion of the study, most subjects reported using the anterior walker frequently to always. In the same survey, 4 out of 10 subjects reported that they preferred the anterior walker over their original posterior walker.

Energy expenditure was determined using the EEI_{HR} method, given by the following expression: EEI_{HR} (beats/meter) = (Average walking HR– Average resting HR) / Walking speed.

A Polar Precision Performance Heart Rate Monitor (model S610, software version 3.02.007, Polar Electro Inc., Woodbury, NY) allowed for the collection of both resting HR and walking HR. Resting HR was collected before gait analysis, and after the subject had been lying in a supine position for 5 minutes. Walking HR was obtained after gait analysis. The subjects walked continuously for five minutes, with HR being recorded. The walking HR value reported was an average of the data from when the HR reached a steady state until the end of the walking period. The distance the subjects walked during this 5-min interval was recorded and used to compute the walking speed. These data were recorded during both anterior and posterior walker trials.

Data analysis

After the raw data was filtered with a Woltring filter, a custom UE kinematic and kinetic model was applied to the data. The kinematic portion of the model was compliant with the International Society of Biomechanics (ISB) UE coordinate system (+X forward, +Y up, and +Z right)[28] and used an Euler rotation method (sagittal-coronal-transverse sequence) to determine joint angles, which were defined as the angle of the distal segment relative to the proximal. Angular velocities and accelerations of each segment were determined by differentiating the position data.

The kinetic portion of the model used the angular velocities and accelerations, along with body segment parameter data and the output from the instrumented handles as inputs. An inverse dynamics approach, similar to Vaughan and Appendix's,[29] was used to calculate joint reaction forces (JRF) and moments (JRM) in each plane for the wrist, elbow, and shoulder (glenohumeral) joints. The JRF for each joint was described in terms of the product of the mass of the distal segment times the acceleration of its center of mass (mass x acceleration)$_{\text{Distal segment}}$, and the force applied to the distal joint ($F_{\text{Distal joint}}$), using the following equation: JRF= (mass x acceleration)$_{\text{Distal segment}} - F_{\text{Distal joint}}$.

The JRMs depend on the rate of change of angular momentum of the distal segment's center of mass ($H_{\text{Distal segment}}$), the moment applied to the distal joint ($M_{\text{Distal joint}}$), and the moment contributions due to the forces at the proximal and distal joints (F) and the moment arms between the segment's center of mass and the joints (R), which is expressed by the following equation: JRM= $H_{\text{Distal segment}} - M_{\text{Distal joint}} - (RxF)_{\text{Proximal joint}} + (RxF)_{\text{Distal joint}}$

Statistical analysis

Biomechanical data were categorized by hand dominance, determined by which hand the subject wrote with. Comparisons between walker types were made with the Wilcoxon signed-rank test. This is a non-parametric test that does not assume linearity and is appropriate for a relatively small sample size. The magnitudes of the peaks (maxima and minima), as well as the dynamic ranges of the forces and moments, were correlated with the EEI_{HR} and gait temporal and stride parameters using Spearman rank correlation coefficients. Because of the large number of comparisons and correlations and to decrease the chance of detecting randomly significant differences, statistical significance was conservatively indicated by a *p* value of less than 0.005.

Results

Energy expenditure

The EEI_{HR} values calculated for each subject are shown in Table 2. In general, anterior walker use was associated with a higher EEI_{HR} (5 of 7 subjects with

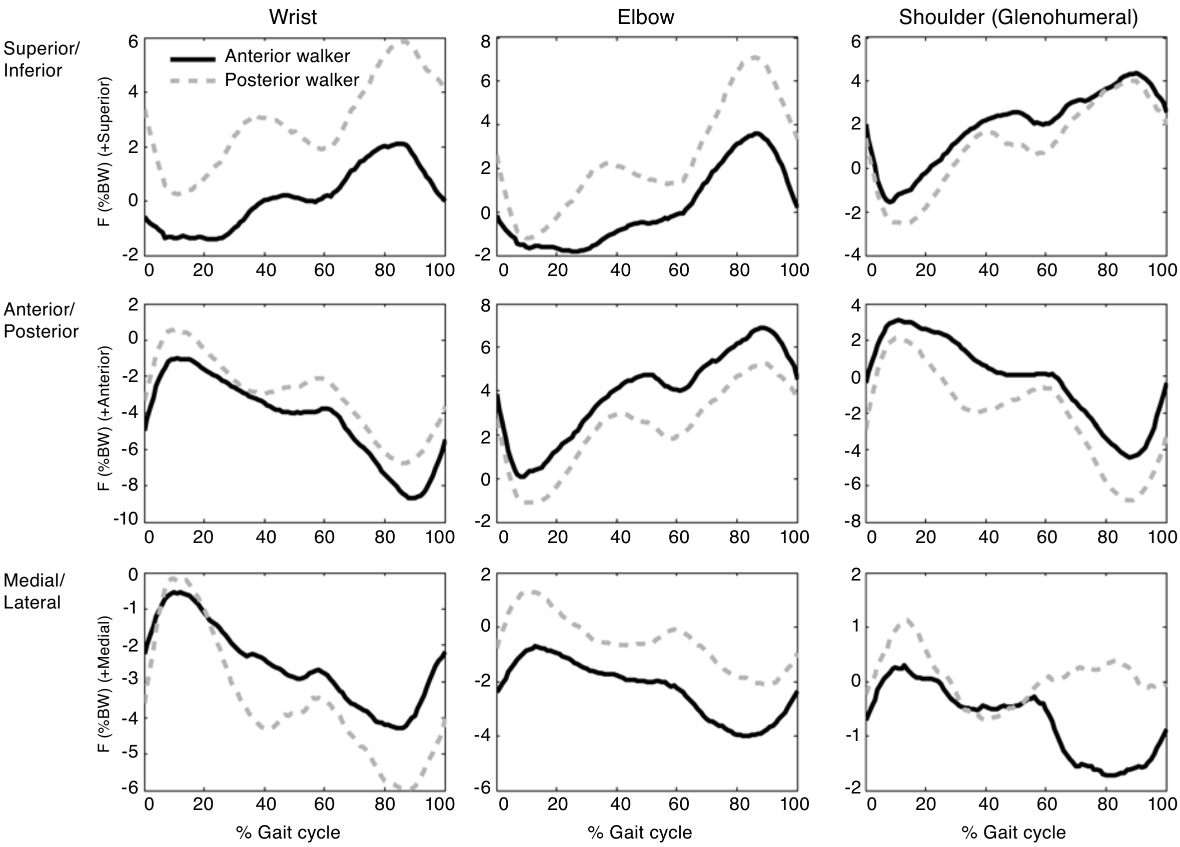

Fig. 2. Average upper extremity joint forces over the gait cycle (both sides combined). BW: Body weight.

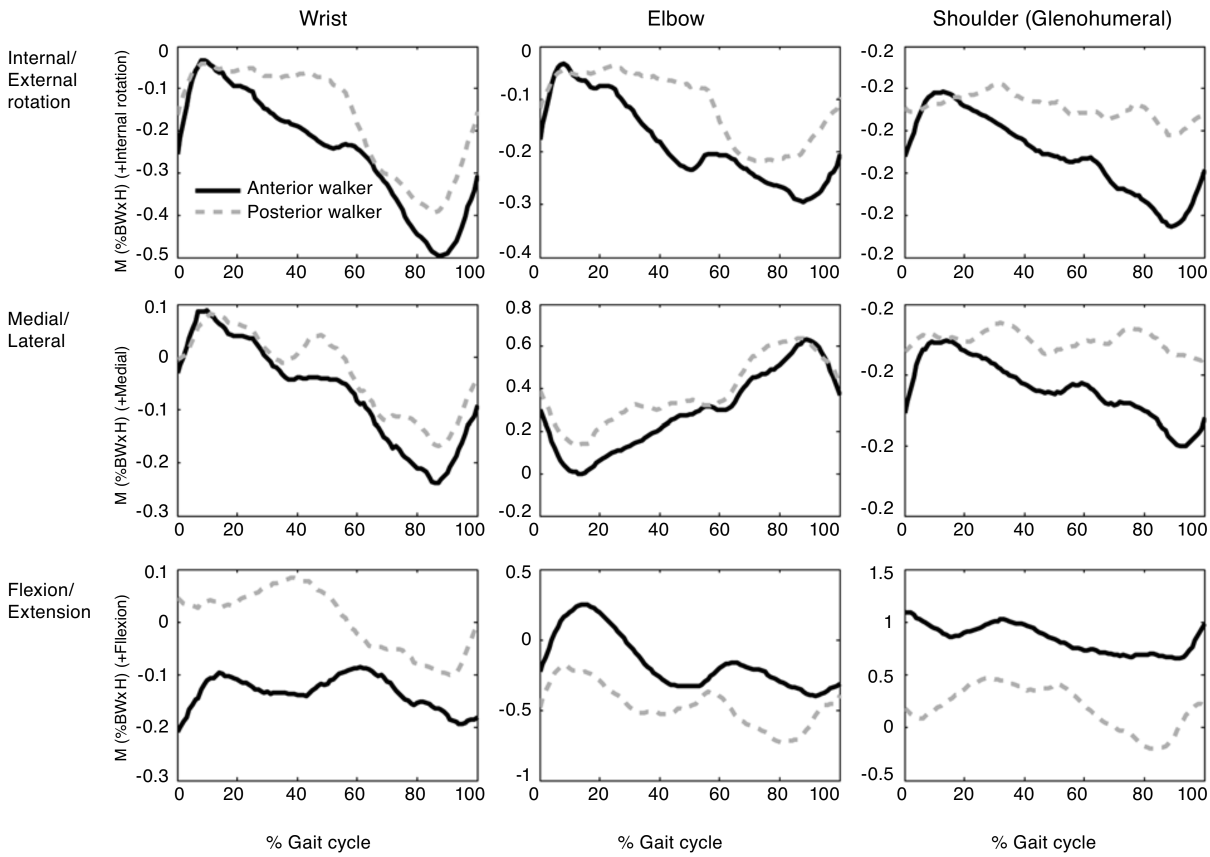

Fig. 3. Average upper extremity joint moments over the gait cycle (both sides combined). BW: Body weight.

complete results). No statistically significant difference was found between the walker types (p=0.47).

Biomechanical data

Average curves for JRFs and JRMs for the 10 subjects are shown in Fig. 2 and Fig. 3, respectively. The data showed few statistically significant differences in the peaks and ranges of loads between anterior and posterior walker use.

Table 2. Energy expenditure index values (beats/meter)

Patient	Anterior walker	Posterior walker
1	0.7	1.1
2	2.6	1.9
3	1.2	0.9
4	1.3	2.6
5	1.5	–
6	1.3	0.5
7	0.5	–
8	7.8	3.4
9	1.2	1.1
10	–	1.0
Mean±SD	2.0±2.2	1.6±1.0

Correlations between joint kinetics and EEI_{HR} were observed in this study (Table 3). All of the significant correlations (r>0.80; p<0.005) occurred during anterior walker use and involved joint reaction forces rather than moments. Forces in all three planes in the non-dominant wrist, and the posterior force in the dominant wrist correlated with EEI_{HR}. The posterior force in the non-dominant elbow, as well as the inferior force in both shoulders also correlated with EEI_{HR}.

Gait temporal and stride parameters

The gait temporal and stride parameters (GTSPs) that were recorded during ambulation with both types of walkers consisted of walking speed, cadence, stride length, and step length. The average and standard deviation values are given in Table 4. The only significant difference in GTSPs between walker types was seen in the left side step length (p=0.0001).

This study showed that several kinetic variables correlated with step length and stride length (r>0.80; p<0.005). These correlations are shown in Table 5. The dynamic range of the internal/external rotation

Table 3. Significant correlations between energy expenditure index and kinetic variables

Joint reaction force		Side	Walker	*r*	*p*
Wrist	Inferior	Non-dominant	Anterior	0.87	0.002
Wrist	Medial	Non-dominant	Anterior	-0.93	0.000
Wrist	Posterior	Dominant	Anterior	-0.87	0.002
Wrist	Superior	Non-dominant	Anterior	0.88	0.002
Elbow	Posterior	Non-dominant	Anterior	0.88	0.002
Shoulder	Inferior	Dominant	Anterior	0.87	0.002
Shoulder	Inferior	Non-dominant	Anterior	0.85	0.004

moment in the dominant elbow also correlated with the cadence bilaterally in posterior walker use. No significant correlations were observed with walking speed in either walker.

Discussion

The purpose of this study was to explore the relationship between energy use and UE joint reaction forces and moments in children with CP using anterior and posterior walkers.

The biomechanical results from this study are reasonable, and are similar in magnitude to those of other UE loading studies. Haubert et al.[2] reported similar shoulder JRFs during adult anterior walker use (*Haubert:* 5.93%BW superior; 3.16%BW inferior; 3.29%BW posterior; 0.92%BW medial; *Current study:* 5.70%BW superior; 4.30%BW inferior; 7.40%BW posterior; 2.30%BW medial). The moments found in this study are similar to those reported by Bachschmidt et al.[12] in the pediatric CP population using walkers (*Bachschmidt et al.:* posterior: 0.15 Nm/kg shoulder flexion, -0.06 Nm/kg elbow extension, 0.02 Nm/kg wrist flexion; anterior: -0.04 Nm/kg shoulder extension, -0.19 Nm/kg elbow extension, 0.07 Nm/kg wrist flexion; *Current study*: posterior: 0.12 Nm/kg shoulder flexion, -0.14 Nm/kg elbow extension, 0.04 Nm/kg wrist flexion; anterior: -0.01 Nm/kg shoulder extension, -0.10 Nm/kg elbow extension, 0.01 Nm/kg wrist flexion). The magnitudes of the moments are also similar to those reported in another study of Bachschmidt et al.[30] in normal adults using a standard anterior walker.

The EEI_{HR} values obtained in this study (average of 1.8 beats/meter) are comparable to those obtained by Raja et al.[14] (1.55 beats/meter) and Toms et al.[20] (2.0 or less beats/meter) in the CP population. Our values are slightly higher than those reported by Keefer et al.[18] (0.50-0.60 beats/meter) and Provost et al.[19] (0.68 beats/meter); however, these studies involved subjects with CP who ambulated without an assistive device.

Several significant correlations were observed between the kinetic variables and EEI_{HR} values or GTSPs. Some of the kinetic variables had multiple correlations across the data set. They were the medial JRF in the wrist, the posterior JRF in the elbow, and the inferior and superior JRFs in the shoulder.

The medial JRF in the non-dominant wrist (Fig. 4a) during anterior walker use was positively correlated with the left step length (r=0.87; p=0.001) and left and right stride lengths (left: r=0.88; p=0.001; right: r=0.89; p=0.001), and negatively correlated with EEI_{HR} (r=-0.93; p<0.001). The medial direction with respect to the wrist points to the ulnar styloid process. Because of the way the hand is positioned on the walker handle, a medial wrist JRF is usually directed to the rear of the walker. This force acts in

Table 4. Gait temporal and stride parameters

	Side	Anterior	Posterior	*p*
Walking speed (m/sec)		0.42±0.06	0.35±0.06	0.1579
Cadence (steps/min)		77.05±7.72	69.79±8.14	0.1662
Stride length (m)	Left	0.64±0.06	0.59±0.05	0.4481
	Right	0.64±0.07	0.60±0.06	0.2731
Step length (m)	Left	0.31±0.04	0.30±0.05	0.0001
	Right	0.32±0.04	0.30±0.04	0.1003

Table 5. Significant correlations between gait temporal and stride parameters and kinetic variables

	Joint	Kinetic variable	Side	Walker	*r*	*p*
Cadence (Left)	Elbow	Internal/external rotation JRM	Dominant	Posterior	-0.85	0.002
Cadence (Right)	Elbow	Internal/external rotation JRM	Dominant	Posterior	-0.84	0.002
Step length (Left)	Wrist	Medial JRF	Non-dominant	Anterior	0.87	0.001
	Elbow	Posterior JRF	Non-dominant	Anterior	-0.92	0.000
	Shoulder	Extension JRM	Non-dominant	Posterior	0.83	0.003
	Shoulder	Inferior JRF	Non-dominant	Anterior	-0.90	0.000
	Shoulder	Superior JRF	Non-dominant	Anterior	-0.93	0.000
Step length (Right)	Wrist	Medial JRF	Non-dominant	Posterior	-0.82	0.004
	Elbow	Medial JRF	Dominant	Anterior	0.81	0.005
	Shoulder	Extension JRM	Dominant	Anterior	0.84	0.002
Stride length (Left)	Wrist	Inferior JRF	Dominant	Posterior	0.84	0.002
	Wrist	Medial JRF	Non-dominant	Anterior	0.88	0.001
	Elbow	Flexion JRM	Non-dominant	Posterior	0.81	0.005
	Elbow	Posterior JRF	Non-dominant	Anterior	-0.85	0.002
	Shoulder	Extension JRM	Non-dominant	Posterior	0.87	0.001
	Shoulder	Inferior JRF	Non-dominant	Anterior	-0.87	0.001
	Shoulder	Lateral JRF	Non-dominant	Anterior	-0.83	0.003
	Shoulder	Superior JRF	Non-dominant	Anterior	-0.90	0.000
Stride Length (Right)	Wrist	Inferior JRF	Dominant	Posterior	0.81	0.005
	Wrist	Medial JRF	Non-dominant	Anterior	0.89	0.001
	Elbow	Posterior JRF	Non-dominant	Anterior	-0.87	0.001
	Shoulder	Extension JRM	Non-dominant	Posterior	0.96	0.000
	Shoulder	Inferior JRF	Non-dominant	Anterior	-0.88	0.001
	Shoulder	Lateral JRF	Non-dominant	Anterior	-0.82	0.004
	Shoulder	Superior JRF	Non-dominant	Anterior	-0.88	0.001

JRF: Joint reaction force; JRM: Joint reaction moment.

response to the hand pushing the walker forward; in other words, it is the reaction to a lateral shear force applied to the wrist by the hand segment. It seems reasonable that if a subject pushes the walker forward with a greater force, the step length and stride length would be greater. This would also lead to a greater gait efficiency, covering more ground with each step, thereby decreasing EEI_{HR}.

The posterior JRF in the non-dominant elbow (Fig. 4b) during anterior walker use was negatively correlated with the left step length (r=-0.92; p<0.001) and right and left stride length (left: r=-0.85; p=0.002; right: r=-0.87; p=0.001), and positively correlated with EEI_{HR} (r=0.88; p=0.002). A posterior JRF in the elbow indicates that the subject may be leaning into the walker frame to advance the body forward. The correlations are reasonable, because if the subject relies on the walker to a greater extent to advance the body forward, he/she will not be able to take very long steps/strides. This pattern would also decrease the distance traveled over time, and therefore increase EEI_{HR}.

The inferior and superior JRFs in the non-dominant shoulder (Fig. 4c) during anterior walker use were negatively correlated with the left step length (superior JRF: r=-0.93; p<0.001; inferior JRF: r=-0.90; p<0.001) and right and left stride lengths (superior JRF, left: r=-0.90; p<0.001; right: r=-0.88; p=0.001; inferior JRF, left: r=-0.87; p=0.001; right: r=-0.88; p=0.001), and the inferior JRF was positively correlated with EEI_{HR} (r=0.85; p=0.004). A superior JRF in the shoulder (along with a posterior JRF) indicates that the subject is pushing down on the walker handle to support the body weight. Because of the extended position of the shoulder, an inferior JRF may be helping to advance the body forward within the walker frame. Greater weight-bearing (as shown by a greater superior JRF) indicates a shorter step/stride length. If a greater force is needed to advance the

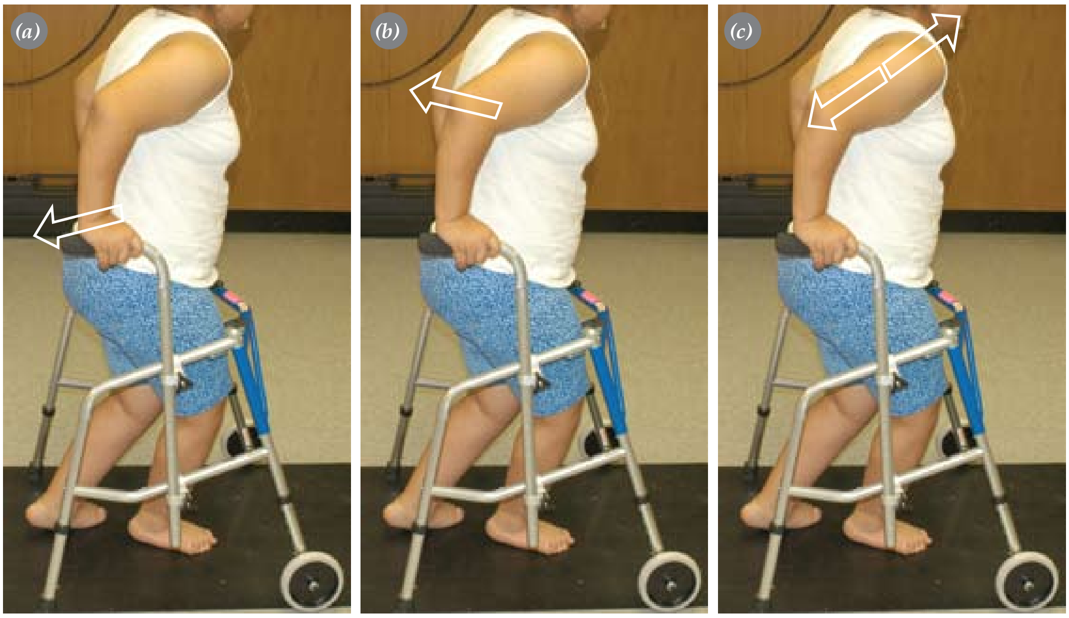

Fig. 4. Joint reaction forces (JRF) in the upper extremity: **(a)** Medial wrist JRF; **(b)** posterior elbow JRF; **(c)** inferior and superior shoulder JRFs.

body forward (inferior JRF), the subject will likely be taking smaller steps/strides. This leads to a less efficient gait and less distance covered over time, and therefore a greater EEI_{HR}.

In general, it seems that the harder the UEs have to work to advance the body forward, the less efficient the subject's gait will be. Conversely, if the subject is using a greater force to advance the walker forward, as seen in the wrist medial JRF, the gait is more efficient.

In the future, work could be done to determine relationships between the kinematics and the kinetics of the UEs during walker-assisted gait. This would lead to a better understanding of how the motion may affect the loading, and vice versa. This would also give a clearer idea of how gait training routines could be changed to optimize UE loading and the efficiency of gait.

Conclusion

Correlations between UE kinetic data during walker use in children with CP and the GTSPs as well as EEI_{HR} were analyzed in this study. Several correlations were observed, including multiple correlations with the medial JRF in the wrist, posterior JRF in the elbow, and inferior and superior JRFs in the shoulder on the non-dominant side when using an anterior walker. Further work needs to be done to understand the reasons for these relationships, and to explore relationships between other variables, including UE kinematics.

Acknowledgements

This project is supported by NIDRR (National Institute on Disability and Rehabilitation Research) grants H133P020004 and H133G010069.

References

1. Yeargin-Allsopp M, Van Naarden Braun K, Doernberg NS, Benedict RE, Kirby RS, Durkin MS. Prevalence of cerebral palsy in 8-year-old children in three areas of the United States in 2002: a multisite collaboration. Pediatrics 2008;121:547-54.
2. Haubert LL, Gutierrez DD, Newsam CJ, Gronley JK, Mulroy SJ, Perry J. A comparison of shoulder joint forces during ambulation with crutches versus a walker in persons with incomplete spinal cord injury. Arch Phys Med Rehabil 2006;87:63-70.
3. Melis EH, Torres-Moreno R, Barbeau H, Lemaire ED. Analysis of assisted-gait characteristics in persons with incomplete spinal cord injury. Spinal Cord 1999;37:430-9.
4. Requejo PS, Wahl DP, Bontrager EL, Newsam CJ, Gronley JK, Mulroy SJ, et al. Upper extremity kinetics during Lofstrand crutch-assisted gait. Med Eng Phys 2005;27:19-29.
5. Bateni H, Maki BE. Assistive devices for balance and mobility: benefits, demands, and adverse consequences. Arch Phys Med Rehabil 2005;86:134-45.
6. Opila KA, Nicol AC, Paul JP. Forces and impulses during aided gait. Arch Phys Med Rehabil 1987;68:715-22.
7. Slavens BA, Frantz J, Sturm PF, Harris GF. Upper extrem-

ity dynamics during Lofstrand crutch-assisted gait in children with myelomeningocele. J Spinal Cord Med 2007;30 Suppl 1:S165-71.

8. Adrezin RS, Cordaro MA, Wang FS, Fast A. Instrumentation and computer interfacing of a standard walker to study user-walker interaction dynamics. In: Proceedings of ASME Bioengineering Division Winter Annual Meeting, Anaheim, CA, Nov 1992. p. 403-5.
9. Fast A, Wang FS, Adrezin RS, Cordaro MA, Ramis J, Sosner J. The instrumented walker: usage patterns and forces. Arch Phys Med Rehabil 1995;76:484-91.
10. Finkel J, Fernie GR, Cleghorn W. A guideline for the design of a four-wheeled walker. Assistive Technology 1997;9:116-29.
11. Pardo RD, Deathe AB, Winter DA. Walker user risk index. A method for quantifying stability in walker users. Am J Phys Med Rehabil 1993;72:301-5.
12. Bachschmidt RA, Harris GF, Hassani S, Carter M, Caudill A, Reiners K, et al. Quantitative study of walker-assisted gait in children with cerebral palsy: Anterior versus posterior walkers. In: Harris GF, Smith P, editors. Pediatric gait: a new millenium in clinical care and motion analysis technology. Piscataway, NJ: Institute of Electrical and Electronics Engineers, Inc.; 2000. p. 217-23.
13. Norman JF, Bossman S, Gardner P, Moen C. Comparison of the energy expenditure index and oxygen consumption index during self-paced walking in children with spastic diplegia cerebral palsy and children without physical disabilities. Pediatr Phys Ther 2004;16:206-11.
14. Raja K, Joseph B, Benjamin S, Minocha V, Rana B. Physiological cost index in cerebral palsy: its role in evaluating the efficiency of ambulation. J Pediatr Orthop 2007;27:130-6.
15. Rose J, Gamble JG, Burgos A, Medeiros J, Haskell WL. Energy expenditure index of walking for normal children and for children with cerebral palsy. Dev Med Child Neurol 1990;32:333-40.
16. Stallings VA, Zemel BS, Davies JC, Cronk CE, Charney EB. Energy expenditure of children and adolescents with severe disabilities: a cerebral palsy model. Am J Clin Nutr 1996;64:627-34.
17. van den Hecke A, Malghem C, Renders A, Detrembleur C, Palumbo S, Lejeune TM. Mechanical work, energetic cost, and gait efficiency in children with cerebral palsy. J Pediatr Orthop 2007;27:643-7.
18. Keefer DJ, Tseh W, Caputo JL, Apperson K, McGreal S, Morgan DW. Comparison of direct and indirect measures of walking energy expenditure in children with hemiplegic cerebral palsy. Dev Med Child Neurol 2004;46:320-4.
19. Provost B, Dieruf K, Burtner PA, Phillips JP, Bernitsky-Beddingfield A, Sullivan KJ, et al. Endurance and gait in children with cerebral palsy after intensive body weight-supported treadmill training. Pediatr Phys Ther 2007;19:2-10.
20. Toms B, Harrison B, Bower E. A pilot study to compare the use of prototypes of multipositional paediatric walking sticks and tripods with conventional sticks and tripods by children with cerebral palsy. Child Care Health Dev 2007; 33:96-106.
21. Maltais DB, Pierrynowski MR, Galea VA, Bar-Or O. Physical activity level is associated with the O_2 cost of walking in cerebral palsy. Med Sci Sports Exerc 2005;37:347-53.
22. Protas EJ, Raines ML, Tissier S. Comparison of spatiotemporal and energy cost of the use of 3 different walkers and unassisted walking in older adults. Arch Phys Med Rehabil 2007;88:768-73.
23. Ulkar B, Yavuzer G, Güner R, Ergin S. Energy expenditure of the paraplegic gait: comparison between different walking aids and normal subjects. Int J Rehabil Res 2003;26:213-7.
24. Park ES, Park CI, Kim JY. Comparison of anterior and posterior walkers with respect to gait parameters and energy expenditure of children with spastic diplegic cerebral palsy. Yonsei Med J 2001;42:180-4.
25. Mattsson E, Andersson C. Oxygen cost, walking speed, and perceived exertion in children with cerebral palsy when walking with anterior and posterior walkers. Dev Med Child Neurol 1997;39:671-6.
26. Strifling KM, Lu N, Wang M, Cao K, Ackman JD, Klein JP, et al. Comparison of upper extremity kinematics in children with spastic diplegic cerebral palsy using anterior and posterior walkers. Gait Posture 2008;28:412-9.
27. Steinwender G, Saraph V, Scheiber S, Zwick EB, Uitz C, Hackl K. Intrasubject repeatability of gait analysis data in normal and spastic children. Clin Biomech 2000;15:134-9.
28. Wu G, van der Helm FC, Veeger HE, Makhsous M, Van Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion-Part II: shoulder, elbow, wrist and hand. J Biomech 2005;38:981-992.
29. Vaughan CL. Appendix B: Detailed mathematics used in GaitLab. In: Vaughan CL, Davis BL, O'Connor JC, editors. Dynamics of human gait. 2nd ed. Cape Town, South Africa: Kiboho Publishers; 1992. p. 83-106.
30. Bachschmidt RA, Harris GF, Simoneau GG. Walker-assisted gait in rehabilitation: a study of biomechanics and instrumentation. IEEE Trans Neural Syst Rehabil Eng 2001; 9:96-105.