Elbow Kinematics During Gait Improve With Age in Children With Hemiplegic Cerebral Palsy

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Background: Children with hemiplegic cerebral palsy (hCP) exhibit a typical posture of elbow flexion during gait. However, the change in elbow kinematics and symmetry during gait across age span in both hCP and typically developing (TD) children is not well described. The aim of this study was to quantify the change in elbow kinematics and symmetry across age span in hCP children compared with TD children.

Methods: Upper extremity kinematic data were extracted and analyzed from a database for gait studies performed between 2009 and 2015. A total of 35 hCP and 51 TD children between the ages of 4 and 18 (mean age: TD = 11.2 ± 0.6, hCP = 9.8 ± 0.5) met inclusionary criteria. The groups were further subdivided into 3 age categories: 4 to 7, 8 to 11, 12+ years old. Elbow angles were extracted and peak elbow flexion, overall range of motion during gait, and asymmetry indices were calculated. A 1-way analysis of variance was performed on each group with post hoc Tukey honestly significant difference pairwise comparisons.

Results: Peak elbow flexion during gait increased with age in TD children ($P < 0.05$) and decreased with age in hCP children on the affected side ($P < 0.05$). There was no change on the less affected side of hCP children. TD children demonstrated significantly less elbow flexion (mean = 51.9 ± 2.1 deg.) compared with the affected side in hCP (mean = 82.1 ± 3.8 deg.) across all age categories ($P < 0.05$). There was no change in elbow asymmetry index (0 = perfect symmetry) across age in either controls or hCP children; however, there were differences between hCP and TD groups in younger age groups (TD = 28, hCP = 62, $P < 0.05$) that resolved by adolescence (TD = 32, hCP = 40).

Conclusions: During gait, hCP children have greater peak elbow flexion on the affected side than do TD children. Peak elbow flexion angle converged between the 2 groups with age, decreasing in hCP children and increasing in TD children. Furthermore, elbow symmetry during gait improves with age in hCP children, approximating symmetry of TD children by adolescence. These findings have implications for both consideration and optimal timing of surgical intervention to improve elbow flexion in children with hCP.

Level of Evidence: Level III—retrospective case-control study.

Key Words: elbow flexion, elbow asymmetry, hemiplegic cerebral palsy, typically developing children, gait analysis, upper extremity surgery timing

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Reciprocal movement of the upper extremity (UE) is an essential component of gait.[1] UE movements enhance gait stability[2] and reciprocal arm swing promotes lateral balance, decreases energy expenditure,[3–5] and improves gait efficiency. Conversely, restricting reciprocal arm swing results in decreased gait velocity[6] and stride length[7] and increased metabolic cost.[8,9]

Little is known about the changes in UE motion across age in typically developing (TD) children and children with spastic hemiplegic cerebral palsy (hCP). Children with hCP have increased shoulder adduction, shoulder flexion, elbow flexion, and wrist flexion that likely has an effect on gait separate from lower limb contributions.[10,11]

In normal development, children's lower extremity (LE) gait kinematics approximate that of adults by 4 years of age.[12,13] The development of LE kinematics in hCP has been studied in this context.[14] Riad et al[15] showed that peak elbow flexion during gait decreased on the hemiplegic side in hCP children with age, but it is not known how closely this approximates elbow motion during gait in TD children. Thus, our understanding of the natural progression of age-related changes in UE movement during gait remains limited. As surgical treatment to decrease elbow flexion spasticity is common, knowledge of the natural history of peak elbow flexion during childhood development is essential to determine the timing and ultimate benefit of surgical treatment in this population.

The purpose of this study was to quantify elbow kinematics and symmetry during gait across age span in TD and hCP children. We hypothesized that peak elbow flexion and asymmetry decline with age in hCP but not in TD children.

METHODS

This study was approved by the Institutional Review Board at the Hospital for Special Surgery on June

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5, 2015 (Study #2015-278 and Study #2015-288). UE kinematic data were extracted and analyzed from a database for gait studies performed between 2009 and 2015.

Subjects

A total of 35 hCP and 51 TD children between the ages of 4 and 18 (mean age: TD = 11.2 ± 0.6, hCP = 9.8 ± 0.5; $P = 0.12$) met inclusionary criteria. TD children were selected from a sample of convenience; those with orthopaedic or neurological disorders were excluded. Exclusion criteria for hCP subjects included: diagnosis of CP after the age of 2 years, dependent use of walkers or crutches, prior UE surgery, LE surgery in the year before gait analysis, treatment of botulinum toxin A to UE or LE 6 months before gait analysis, and Gross Motor Function Classification System (GMFCS) level greater than II.

Physical therapy notes were reviewed, and demographic and clinical data were extracted including age, sex, side of involvement, GMFCS status, prior history of UE or LE surgery, prior history of botulotoxin A treatment, and age of CP diagnosis.

Procedure

Gait analysis data were extracted from a database of gait studies. All gait studies utilized a 12-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA). Thirty-five retroflective markers were placed on each subject's UEs, trunk, pelvis, and LEs using the Cleveland Clinic Marker set (OrthoTrak Manual; Motion Analysis Corporation, 2007). Three-dimensional kinematics were captured at 100 Hz. Joint kinematics were calculated in OrthoTrak (version 6.55; Motion Analysis Corporation). An average of 10 representative gait cycles were collected as subjects walked at self-selected walking speed.

Analysis

Gait cycles were normalized to time, and peak elbow flexion, extension and overall range during each cycle was calculated. Peak elbow flexion was defined as maximum elbow flexion achieved during gait testing. Elbow range (ie, total arc of motion) was defined as elbow range of motion excursion during gait and was calculated as the difference between maximum elbow flexion and maximum elbow extension during gait analysis. An asymmetry index was used to quantify differences between the 2 limbs. Elbow asymmetry indices (ASI) were calculated according to following formula[16]:

$$\text{ASI} = \text{Absolute value } [2\times(\text{right value} - \text{left value})/(\text{right value}+\text{left value})]\times 100.$$

An ASI closer to 0 indicates more symmetrical movement of the UEs during gait.

To analyze elbow motion across age, both TD and hCP groups were subdivided into 3 age categories, 4 to 7, 8 to 11, and 12+ years of age.[17] For the hCP subjects, data were analyzed separately for the affected and less affected arm. For TD children, the mean of both arms was used.

Descriptive statistics are presented as means and SE of the mean for continuous variables and frequencies and percentages for categorical variables. Differences in kinematic variables and ASI among age groups were assessed separately for TD and hCP groups with single-factor analysis of variances with post hoc Tukey honestly significant difference tests. If non-normally distributed, Kruskal-Wallis tests with Bonferroni-corrected post hoc Mann-Whitney U tests were used.[18] Differences in ASI between TD control and hCP groups were assessed with independent sample T tests, or Mann-Whitney U tests when non-normally distributed. An analysis of covariance was performed on gait velocity. The level of significance for all tests was 0.05. All statistical analyses were performed using IBM SPSS Statistics; Armonk, NY (version 19.0).

RESULTS

There were no differences in age and sex between both groups and subgroups. A detailed description of age breakdown per subgroup and overall demographics is provided in Table 1.

Elbow Posture Improves in Affected Side of hCP Children With Age

Peak elbow flexion significantly increased in TD children with age ($P = 0.002$) from 46 degrees in both 4 to 7 and 8 to 11 age groups to 59 degrees in the 12+ age group (Fig. 1). hCP children displayed no change in peak elbow flexion with age on the less affected side. On the affected side, peak elbow flexion decreased with age, with the 4 to 7 age group demonstrating increased flexion compared with both the 8 to 11 and 12+ age groups ($P = 0.006$).

hCP children demonstrated increased peak elbow flexion on both sides compared with the TD group in both 4 to 7 and 8 to 11 age categories ($P < 0.001$). In the 12+ age group, peak elbow flexion was greater on the affected hCP side compared with the less affected side and compared with TD children ($P = 0.01$).

Elbow Range in hCP Children Approximates TD Children by Adolescence

Overall elbow range during gait did not change within the TD or hCP groups across age. However, between-group comparisons showed differences between the TD group and affected hCP side in the 4 to 7 and 8 to 11 age categories. A greater amount of elbow motion was present in the TD population compared with the hCP affected arm in both the 4 to 7 ($P = 0.02$) and 8 to 11 ($P = 0.008$) age groups (Fig. 2). These differences were no longer present in the 12+ age group, indicating resolution by adolescence.

Elbow Asymmetry Index (ASI) in hCP Children approximates TD Children by Adolescence

Elbow ASI did not change within the TD or hCP group across age (Fig. 3). However, comparisons between the subgroups indicated a greater elbow ASI in the hCP

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TABLE 1. Demographics

	Controls (N = 51)	hCP (N = 35)	*P*
Age (y)	11.2 ± 0.6	9.8 ± 0.5	0.12
Age categories (y)	4-7 (n = 11) 8-11 (n = 18) 12+ (n = 22)	4-7 (n = 8) 8-11 (n = 16) 12+ (n = 11)	NA
Sex (%)	Male: 52.9 (n = 27) Female: 47.1 (n = 24)	Male: 57.1 (n = 20) Female: 42.9 (n = 15)	0.70
Affected side (%)	NA	Left: 68.6 (n = 24) Right: 31.4 (n = 11)	NA
GMFCS (%)	NA	I: 48.6 (n = 17) II: 51.4 (n = 18)	NA

GMFCS indicates Gross Motor Function Classification System; hCP, hemiplegic cerebral palsy; NA, not available.

population compared with TD counterparts in the 8 to 11 group ($P = 0.006$). This difference resolved in the 12+ group.

Gait Velocity is Not a Confounding Factor for Development Changes in Gait

To control for the effect of gait velocity on elbow position, an analysis of covariance was performed for all 3 groups (TD controls, less affected hCP arm, affected hCP arm) with age as the independent variable and gait velocity as the covariate. All previous results remained the same. TD controls once again demonstrated increased elbow flexion with increased age ($P = 0.004$), and elbow flexion decreased in the affected arm of hCP patients, with the 4-7 year old group having significantly increased flexion compared with both the 8-11 and 12+ age groups ($P = 0.02$).

DISCUSSION

Elbow flexion posture caused by spasticity in the elbow flexors is the most common elbow deformity in children with hCP.[19] Interventions to improve elbow extension during both functional activities and gait range from conservative management, such as therapy, serial casting, and botulinum toxin injections, to surgery.[20] Surgery is performed to increase elbow extension and improve the elbow flexion angle during gait.[21,22] Although surgery often successfully achieves these aims and is generally satisfying to the patient and family, it is still unclear how much improvement can occur without intervention. In this study, we showed that the change in elbow posture and symmetry during gait improves with age in children with hCP.

Elbow surgery continues to be performed at a young age (mean age = 8.7, 9 y, respectively) in children with hCP.[21,22] These studies report significant improvement in achieving and maintaining peak elbow flexion angle. Because there is improvement in elbow extension over time without intervention, it may be preferable to

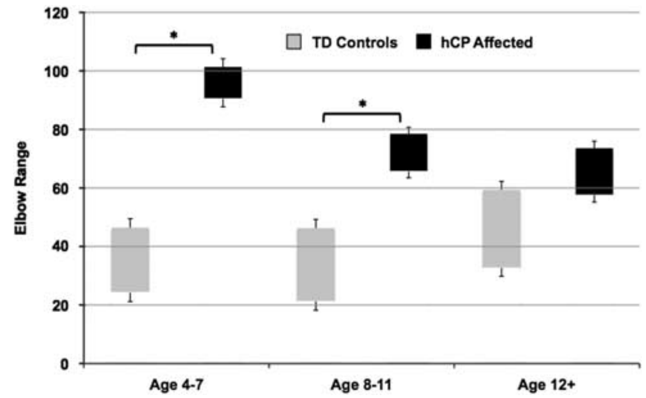

FIGURE 2. Elbow range during gait in typically developing (TD) and hemiplegic cerebral palsy (hCP) children. *TD children have significantly more elbow range compared with hCP affected arms at age 4 to 7 and 8 to 11 ($P<0.05$) that resolves by adolescence.

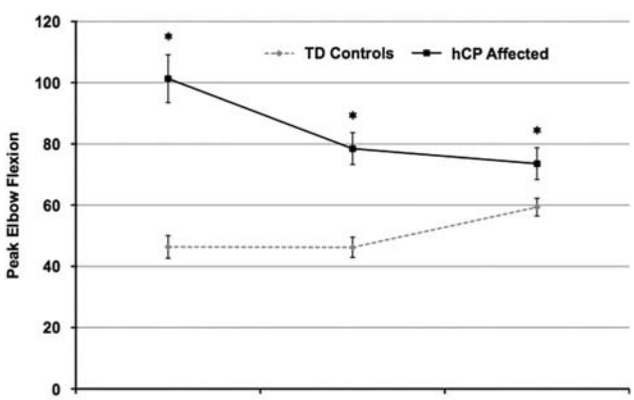

FIGURE 1. Peak elbow flexion during gait in typically developing (TD) and hemiplegic cerebral palsy (hCP) children. *hCP affected arms have significantly more elbow flexion compared with TD children, across all age groups ($P<0.05$). As age increases, peak elbow flexion significantly decreases in the hCP affected arm, compared with TD controls.

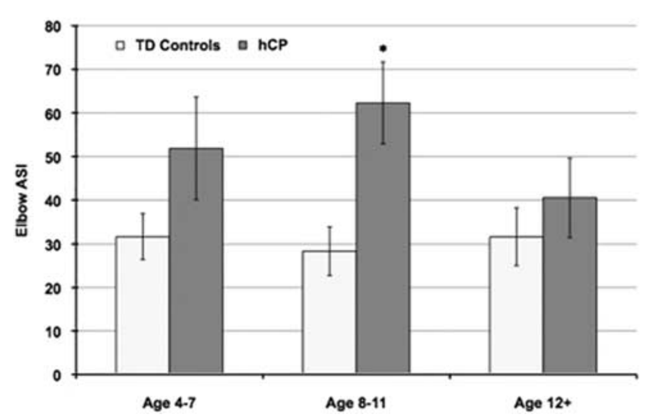

FIGURE 3. Elbow asymmetry index (ASI) during gait in typically developing (TD) and hemiplegic cerebral palsy (hCP) children. *hCP children have significantly more asymmetry than TD controls at age 8 to 11 ($P<0.05$) that resolves by adolescence.

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perform elbow release surgery later in adolescence. In our cohort, by age 12+, both elbow posture and asymmetry improved approximating that of TD children, suggesting that there may be benefit to delaying surgery.

Though anterior elbow release is an effective method to improve elbow flexion in hCP children, based on our results, we suggest a conservative, patient-centered approach to surgical intervention, especially in young children who may still have improvement in elbow flexion with age. Surgical management would still be indicated in children who no longer demonstrate improvement in elbow extension and have achieved growth potential, or those who wish for a more immediate aesthetic benefit. Alternatively, botulinum toxin injections may be offered as a temporary measure to reduce peak elbow flexion until hCP children experience spontaneous decline in peak elbow flexion with age.

There were limitations to our study. We retrospectively analyzed a cohort of children across an age range whereas a longitudinal study of the same cohort of children would be more conclusive. Furthermore, a comparison of GMFCS levels within each hCP age group could provide additional information; however, our sample size was too small to provide valuable data. Lastly, as a retrospective and cross-sectional study, we were limited to demographic data in our database that includes a diagnosis of hemiplegia, but we were unable to quantify differences in baseline spasticity based on this data. For this same reason, we were unable to ascertain whether hemiplegic patients had prior fixed elbow contractures.

In conclusion, elbow flexion spontaneously decreases on the affected side during gait in hCP children. This reduction in elbow flexion is unlike that seen in normal development, and hence, is likely a component of the natural progression of hCP. These findings indicate that patients wishing to undergo surgery to improve the aesthetic of the affected hCP elbow may be better served by waiting until adolescence, given the spontaneous improvement in elbow position in many cases.

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