Are Muscle Volume Differences Related to Concentric Muscle Work During Walking in Spastic Hemiplegic Cerebral Palsy?

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Abstract

Background Individuals with spastic hemiplegic cerebral palsy are typically high functioning and walk without assistive devices. The involved limb is usually smaller and shorter, although it is not clear whether the difference in muscle volume has an impact on walking capacity.

Questions/purposes We determined the volume of muscles important for propulsion and related that volume to concentric muscle work during walking on the hemiplegic and noninvolved sides in patients with cerebral palsy.

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

The work was performed at Skaraborg Hospital and Karolinska Institutet.

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Patients and Methods We studied 46 patients (mean age, 17.6 years; range, 13–24 years) with spastic hemiplegic cerebral palsy. We assessed muscle volume using MRI and concentric muscle work in the sagittal plane from the hip, knee, and ankle using three-dimensional gait analysis. Patients were classified by Winters' criteria to assess the involvement of cerebral palsy and movement pattern during walking.

Results On the hemiplegic side, muscles were smaller, except for the gracilis muscle, and concentric muscle work from the ankle plantar flexors, knee extensors, and hip flexors and extensors was lower compared to the noninvolved side. Hip extensor work was higher on the hemiplegic and the noninvolved sides compared to a control group of 14 subjects without cerebral palsy. Hemiplegic to noninvolved volume ratios correlated with work ratios ($r = 0.40$ – 0.66). The Winters classification and previous calf muscle surgery predicted work ratios.

Conclusions Our observations of smaller muscles on the hemiplegic side and changes in muscle work on both sides can help us distinguish between primary deviations that may potentially be treatable and compensatory mechanisms that should not be treated.

Introduction

Of all patients with cerebral palsy (CP), those with spastic hemiplegic CP tend to have the best walking capacity [7, 16]. Nevertheless, these high-functioning individuals often have a noticeable asymmetry and deviant movement pattern during walking [13, 22]. The impaired motor control with increased muscle tone also influences movement on the noninvolved side. It is difficult not only to define

deviations in movement pattern but also to separate them from compensatory mechanisms the patient has developed. Ideally, the compensatory mechanisms should not be treated, but rather the underlying cause, even though the primary brain injury cannot be rectified [7, 16, 26]. Treatment is seldom considered in these patients, partly because the impairment is mild and partly because effective treatment options are limited. Targeted muscle strengthening and coordination exercise programs, combined with focal muscle lengthening and bone realignment in specific cases, may provide improvement [3, 7, 16, 25].

The involved limb in spastic hemiplegic CP is usually smaller and shorter than the other limb. It is not clear whether this difference is due to the brain injury, impaired nerve innervations and influence on growth factors, or reduced mechanical use. Several studies show muscle volume correlates with strength, and training is beneficial in CP [1, 6]; however, age, severity of involvement, and degree of improvement in strength and gait vary greatly in these studies [1, 2, 6, 18]. Elder et al. [5] reported an inability to perform voluntary maximal contractions contributed to muscle weakness in patients with CP.

Three-dimensional (3-D) gait analysis (GA) reveals aberrant movement (kinematics) in the pelvis, hip, knee, and ankle of patients with CP, depending on the severity of deviations [7, 16]. Those with mild hemiplegic CP most frequently show deviations in the sagittal plane in ankle movement when assessed with GA, although the deviations can be very subtle [4, 14, 23, 30]. On the other hand, kinetic data from GA, including calculations of forces acting over the joints derived from force plates, can reveal decreased moments, mistimed pathologic moments in the gait cycle, and decreased muscle work. Concentric muscle work, also called positive muscle work, is defined as the sum of power generation a muscle produces when it shortens and, in the sagittal plane, is considered to be responsible for propulsion in gait [16, 24]. Kinetic data that include concentric muscle work might be the key to understanding deviations in movement patterns and distinguishing compensatory mechanisms and could in addition be of help to develop and evaluate treatment strategies [8, 12, 26, 27].

Smaller muscle volumes have been found on the hemiplegic compared to the noninvolved side. [10]. In addition, during gait, a bilateral shift of concentric muscle work from ankle plantar flexors to hip extensor muscles reportedly occurs in children with hemiplegic CP [24]. Although there are reports on muscle volume and muscle work, it is still unclear whether and how muscle volume influences gait [5, 10, 12, 24].

We therefore (1) determined muscle volume and muscle work differences between the hemiplegic and noninvolved sides, (2) examined possible correlations between these

differences in anatomic muscle volume and dynamic muscle work during walking, and (3) explored other variables that could have an influence on the correlations.

Patients and Materials

For this cross-sectional, observational study, we recruited a convenience sample of 46 patients from the neuromuscular clinics and databases of two hospitals in Sweden. We performed a power analysis, in which we took into consideration other variables to be studied but not reported here. Power analysis for 80% power required around 20 patients regarding muscle volume, which is in line with Lampe et al. [10], who included 16 participants and found statistical differences. Correspondingly, muscle work differences calculated for ankle plantar flexors with a decrease of 33% required around 25 patients.

We sent a letter of information and an invitation by mail. Two to 3 weeks later, we contacted the patients by telephone, and if they indicated willingness to participate, their eligibility was reconfirmed against the inclusion and exclusion criteria. All paid a single visit to the same hospital where the 3-D GA and MRI were performed. The study included 46 patients with spastic hemiplegic CP (mean age, 17.6 years; range, 13–24 years) (Table 1).

Table 1. Baseline characteristics of 46 participants with spastic hemiplegic cerebral palsy

Variable	Value
Age (years)*	17.6 (3.3)
Female/male (number)	22 (48%)/24 (52%)
Hemiplegic side left/right (number)	16 (35%)/30 (65%)
Weight (kg)*	62.2 (16.1)
Height (cm)*	167.4 (9.6)
Tibia leg length discrepancy (mm)*	8.1 (6.4)
Femur leg length discrepancy (mm)*	0.6 (5.2)
Gross motor function classification (number)	
I	44
II	2
Winters classification (number)	
Type 0	21
Type 1	24
Type 3	1
Previous calf muscle surgery (number)	19 (41%)
Achilles tendon lengthening (number)	
Once	10 (22%)
Twice	4 (9%)
Three times	3 (7%)
Achilles tendon + Strayer lengthening once (number)	2 (4%)

* Values are expressed as mean, with SD in parentheses.

Twenty-two were female and 24 male; 16 had left side involvement and 30 had right side involvement. Inclusion criteria were spastic hemiplegic CP (unilateral) with a diagnosis before the age of 2 years; a current age of 13 to 24 years old; and the ability to cooperate during GA (1.5 hours), undergo MRI (30 minutes), and answer questions from the questionnaires with some assistance. Exclusion criteria were any disease or previous injury affecting gait, metal implants (contraindication for the MRI), substantial developmental delay (see above), previous lower-extremity surgery other than calf muscle lengthening, and surgery or spasticity treatment (botulinum toxin) within the last year. For a control group, we recruited 14 sex- and age-matched subjects from friends' and colleagues' families, using the same exclusion criteria as for the study group. We obtained ethical approval for the study in accordance with the ethical standards in the Declaration of Helsinki. Participants (and their parents if subjects were younger than 18 years) gave informed consent before inclusion.

We collected baseline data and patients were classified using a modification [23] of the classification of Winters et al. [30] (Table 1). The modification includes the least involved patients (Type 0), and in this study, 21 of the 46 patients had the mildest form.

We completed GA on the 46 patients with CP and the 14 control subjects. We also completed MRI testing and analysis on 30 of the 46 patients with CP ($n = 15$ males and 15 females).

We performed 3-D GA and recorded gait with a Vicon eight-camera 3-D motion analysis system (Vicon Motion Systems, Ltd, Oxford, UK). We placed reflective markers on bony landmarks or specific anatomic positions (Plug-in-Gait model; Vicon Motion Systems) and calculated a mean of three cycles with SD. The patient walked at a self-selected speed on a 10-m walkway. Two force plates (Kistler, Winterthur Wülflingen, Switzerland) collected the ground reaction force vectors. Joint power was divided into three components, corresponding to each anatomic plane, and concentric muscle work (positive work) was calculated as the cumulative sum of power generation in each plane. Concentric muscle contraction for propulsion occurred mainly in the sagittal plane of the hip, knee, and ankle and was calculated as the area under the curve above the zero line [24] (Fig. 1). To compare and correlate the differences in muscle volume and work, we performed calculations on the ratio of the muscle volume or work of the hemiplegic side divided by that of the noninvolved side. Additionally, muscles contributing to the concentric muscle work were identified and allocated to one of the following muscle groups: plantar flexors, with the gastrocnemius, soleus, and smaller flexors, including the tibialis posterior and toe flexors; the knee extensors, with the quadriceps muscle; the hip extensors, with the gluteus maximus; and the hip

flexors, with the sartorius, gracilis, adductors, and iliopsoas muscles (Fig. 1).

Using a Philips Achieva 1.5-T MRI system (Philips Medical Systems, Best, The Netherlands), we examined the patient who was in a supine position, with both lower limbs fully extended and parallel to the long axis of the body. To measure muscle volume, we acquired consecutive axial images, T2 weighted, from the highest insertion of the psoas (midthorax) muscle to the sole of the feet. Slice thickness was 5 mm with 10-mm gaps between slices.

The volume of the dorsi and plantar flexors and the individual muscles that compose the hips and thighs were analyzed using custom software developed with Interactive Data Language (Research Systems, Inc, Boulder, CO) and the following procedure. First, the individual muscles in each raw image were traced over the muscle boundary and labeled appropriately. Images were filtered and image segmentation was performed with a fuzzy clustering algorithm to separate muscle from other tissues, such as adipose tissue and bone [9, 28]. Pixels identified as muscle were summed and the cross-sectional area for each muscle in each image was calculated. The volume of each muscle was estimated by multiplying the cross-sectional areas by 1.5 to account for the thickness of the image (0.5 cm) and the space between images (1.0 cm) (Fig. 2). To determine the interobserver reliability for estimating muscle volume using MRI, four hemiplegic sides and four noninvolved sides from participants were evaluated by two different research assistants (hips: EK, KMR; thighs: EK, BM; shanks: DB, BM) and estimates were compared. The coefficients of variation for repeat assessment of muscle volume were 4.8% for dorsiflexors, 4.5% for plantar flexors, 2.8% for rectus femoris, 2.7% for quadriceps, 2.4% for biceps femoris, 3.5% for semimembranosus, 3.5% for semitendinosus, 2.9% for sartorius, 3.5% for gracilis, 3.9% for adductors, 3.9% for adductor longus, 3.8% for gluteus maximus, 5.2% for gluteus medius, and 4.8% for iliopsoas.

Descriptive statistics were computed as mean, SD, and ratio of the hemiplegic and noninvolved sides for numerical variables or as percentages for categorical variables. A paired t test was used to determine differences in means between the hemiplegic and noninvolved sides and between the patient and control groups. When the distribution deviated from normality, we applied the Wilcoxon signed-rank test. The Pearson correlation coefficient was used to measure the strength of linear association between muscle work and muscle volume ratios. Using multiple linear regression analysis, we estimated the relationship between the muscle work and muscle volume ratios of the hemiplegic and noninvolved sides, while controlling for other demographic and clinical variables. In the model, we used the standard or simultaneous method and included variables with known clinical importance. Muscle work

Fig. 1A–C The graphs show (A) mean ankle plantar flexor work, (B) mean knee extensor work, and (C) mean hip extensor and hip flexor work for the 46 patients with spastic hemiplegic CP. The solid line represents the mean values for the hemiplegic side, and the dotted line represents the mean values for the noninvolved side. The concentric muscle work is calculated as the positive area under the curve (above the horizontal zero line).

Fig. 2 A MR image of the thighs and shanks show muscle size differences between the hemiplegic and noninvolved sides.

was the primary outcome variable. The predictor variables were muscle volume ratio of the hemiplegic and noninvolved sides, age, previous calf muscle surgery, modified classification of Winters et al. [23, 30], walking speed, tibia length discrepancy, and femur length discrepancy. We performed an interaction test and checked for multicollinearity problems. We considered a variation inflation factor of greater than 4 as a cutoff criterion for deciding when a given predictor variable displayed “too great” a multicollinearity problem. A Durbin-Watson coefficient between 1.5 and 2.5 indicated independence of observations. We considered a Cook’s distance value of $D > 4/n - k - 1$ as a criterion to indicate a possible outlier problem (n = sample size, k = number of predictors). The final model, showing only the significant results (parsimonious model) for each outcome variable, is presented below. The model-building procedure and the guidelines for reporting regression analysis are described in detail elsewhere [11]. SPSS® Version 18.0 (SPSS Inc, Chicago, IL) was used for all data analyses.

Results

All muscles on the hemiplegic side, from the iliopsoas muscle to the plantar and dorsiflexors of the shank, had a lower volume ($p < 0.001$; gluteus medius: $p = 0.021$), compared to the noninvolved side, except the gracilis ($p = 0.176$). The differences between hemiplegic and noninvolved sides were generally larger as indicated by smaller ratios of the hemiplegic side to the noninvolved in the distal muscles than in the proximal muscles (Table 2).

Concentric muscle work was also lower on the hemiplegic side compared to the noninvolved side for the ankle plantar flexors, knee extensors, and hip flexors ($p < 0.001$) and for the hip extensors ($p = 0.028$). The hip extensor work was increased on the hemiplegic ($p = 0.05$) and noninvolved ($p < 0.001$) sides compared to the nondominant and dominant sides, respectively, in the control group.

We found correlations between the muscle work and muscle volume ratios. For the ankle plantar flexor muscle, the muscle volume ratio correlated ($r = 0.403$; $p < 0.05$) with the concentric muscle work ratio. Correspondingly, there were correlations between the knee extensor muscle volume and work ratios ($r = 0.655$; $p < 0.01$) and between the adductor muscle volume and work ratios ($r = 0.578$; $p < 0.05$).

Concerning other variables with possible influence, walking speed normalized to leg length (mean, 1.36 m/second; SD, 0.28 m/second) had no influence. The plantar flexor volume ratio and previous calf muscle surgery predicted increased ankle plantar flexor work ratio (adjusted $R^2 = 0.347$). For the knee extensor work ratio, only the quadriceps volume ratio was a predictor ($R^2 = 0.388$). A higher type in the modified classification of Winters et al. [30] predicted an increase and previous calf muscle surgery predicted a decrease in hip extensor work ratio (adjusted $R^2 = 0.404$). For the hip flexor work ratio, the medial hamstring volume ratio was the only predictor ($R^2 = 0.278$) (Table 3).

Discussion

Patients with spastic hemiplegic CP often show differences in leg size and deviant movement patterns. It is unclear whether the difference in muscle volume has an impact on gait. Detecting gait deviations based solely on kinematic data from GA in high-functioning patients can be difficult, whereas kinetic data more readily reveal deviations from normal. The deviations in the kinetic data can be useful in identifying abnormalities and helping to develop and evaluate treatment strategies. In this study, we determined muscle volume and muscle work differences between the hemiplegic and noninvolved sides in patients with spastic hemiplegic CP and studied correlations between these differences. Other factors that could potentially influence the correlations were also studied.

We note limitations to this study. First is the relatively small number of subjects ($n = 46$), of whom muscle volume was estimated in only 30 patients. Muscle volume measurement with MRI is relatively expensive and time consuming [29]. Analysis of a control group would be useful in allowing comparison of differences in the patients’ leg size to that in the normal population. Second,

Table 2. Descriptive statistics and bivariate paired t test

Muscle	Hemiplegic side	Noninvolved side	Ratio hemiplegic/ noninvolved	Bivariate paired t test	
				95% CI of difference	p Value
Muscle volume (cm ³) (n = 30)					
Dorsiflexors	151 (35)	212 (57)	0.712	47–74	< 0.001
Plantar flexors	782 (233)	1070 (299)	0.731	221–356	< 0.001
Rectus femoris	194 (58)	246 (82)	0.789	38–66	< 0.001
Quadriceps	1306 (312)	1675 (470)	0.780	288–450	< 0.001
Biceps	208 (53)	255 (71)	0.816	32–62	< 0.001
Medial hamstrings	492 (132)	581 (161)	0.847	–3–13	< 0.001
Semimembranosus	156 (47)	182 (50)	0.857	6 –21	0.001
Semitendinosus	128 (46)	144 (48)	0.889	15–37	< 0.001
Sartorius	134 (41)	147 (49)	0.912	9–22	< 0.001
Gracilis	84 (28)	90 (23)	0.933	63–115	0.176
Adductors	537 (163)	683 (207)	0.786	9 –19	< 0.001
Adductor longus	102 (40)	116 (44)	0.879	121–171	< 0.001
Gluteus maximus	597 (168)	709 (200)	0.842	1–16	0.021
Gluteus medius	245 (61)	254 (64)	0.965	89–135	< 0.001
Iliopsoas	341 (92)	360 (99)	0.947	11–28	< 0.001
Concentric muscle work (J/kg) (n = 46)					
Ankle: plantar flexors	0.211 (0.064)	0.350 (0.083)	0.603	0.114–0.164	< 0.001
Knee: quadriceps	0.075 (0.036)	0.154 (0.055)	0.487	0.064–0.094	< 0.001
Hip extensors: gluteus maximus	0.090 (0.050)	0.111 (0.057)	0.811	0.002–0.038	0.028
Hip flexors: medial hamstrings, adductors, iliopsoas	0.150 (0.046)	0.209 (0.056)	0.718	0.041–0.077	< 0.001

Values are expressed as mean, with SD in parentheses; CI = confidence interval.

Table 3. Results of linear regression model for the relationship between the muscle work ratio and predictor variables

Variable	R ²	b	SE	p value	95% CI for b
Ankle plantar flexor work ratio					
Plantar flexor volume ratio	0.347	1.06	0.26	< 0.001	0.54, 1.59
Previous calf muscle surgery		0.19	0.07	0.02	0.04, 0.34
Knee extensor work ratio					
Quadriceps volume ratio	0.388	2.62	0.62	< 0.001	1.34, 3.89
Hip extensor work ratio					
Winters classification	0.405	0.61	0.13	< 0.001	0.35, 0.87
Previous calf muscle surgery		–0.35	0.16	0.04	0.67, –0.02
Hip flexor work ratio					
Hamstring volume ratio	0.278	1.14	0.35	0.003	0.43, 1.85

The model tested the following variables: muscle volume ratio of the hemiplegic and noninvolved side, age, previous calf muscle surgery, Winters classification, walking speed, tibia leg length discrepancy, and femur leg length discrepancy; only significant findings are presented; R² = regression correlation coefficient; b = regression coefficient; SE = standard error; CI = confidence interval.

the MRI analysis technique was not completely automated (ie, the boundaries of the muscles were selected manually); however, MRI has been shown to provide accurate estimates of muscle volume [17]. The software used in our study has been validated by Modlesky et al. [19], and the interrater reliability of individual muscle volume assessment was good, as indicated by coefficients of variation 5% or less. Third, capturing and quantifying movements in three dimensions as part of the calculation of the kinetic data involve several problems, including lack of subject-specific models and possible inconsistency of marker placement. The impact of these variables and the subject awareness of the recording of gait in the laboratory environment are difficult to assess.

Our results are consistent with those of previous studies reporting muscles are smaller on the hemiplegic side and the differences are more pronounced distally in the limb [5, 10]. We cannot conclude whether the differences in muscle volume arise because brain injury alters patterns of innervation and growth factor release or because of disuse, with less work performed over the joints and growth plates in the hemiplegic limb.

Our current findings on concentric muscle work confirm those in a previous study that showed increased compensatory hip extensor work on both sides and decreased plantar flexion work on the hemiplegic side in a younger group of children with hemiplegic CP (mean age, 8.4 years) [24]. Similar findings on the hemiplegic side were also reported by Olney et al. [20].

Several groups have reported muscle volume correlates with strength and muscle strengthening is possible in patients with CP [2, 3, 6, 15, 18]. Published studies are few and vary greatly in terms of outcomes; thus, it is difficult to compare the effects of different muscle-strengthening strategies. Our results show a clear correlation between muscle volume and concentric muscle work during walking. The clinical implication is that muscle-strengthening programs might be of value, although it is not clear which muscles should be strengthened to improve gait. In addition, orthopaedic surgical treatment can be considered, and our results reveal clinically important information on the adductor longus and the rectus femoris muscles. Surgery to lengthen the adductor longus muscle can be considered when increased muscle tone and spasticity cause excessive adduction and flexion in the hip. Surgery can also alleviate the “stiff knee gait” caused by prolonged contraction of the rectus femoris muscle. Such contraction leads to decreased and delayed knee flexion in swing, with the typical toe-drag and compensatory hip circumflexion of the limb to clear the foot in swing. Under these circumstances, the rectus femoris can be transferred to remove deforming and mistimed forces [21]. The orthopaedic treatment team might be concerned these procedures will cause the patient to lose strength. The risk of weakening, for example, the important extensor muscles must always be considered. Our results show the adductor longus and rectus femoris muscles are small and contribute relatively little to the total muscle volume of the hip flexors and the knee extensors, respectively (Fig. 3). Moreover, the volume ratio and the work ratio are fairly equal. Therefore, we suspect lengthening would most likely not cause major loss of strength in this situation (Fig. 4).

Another factor of interest is previous surgical lengthening of the calf muscle, which increased the ratio of muscle work in the ankle plantar flexors. One interpretation is that the foot is better positioned after surgery and can generate more work, which partially normalizes the ratio. In the hip, the change is in the opposite direction: there is a small reduction of the hip extensor work ratio after surgical lengthening of the calf muscle.

As one moves from Type 0 to Type 1 in the modified Winters classification, the ratio of muscle work in the hip extensors increases. This might be an expression of symmetrical compensatory recruitment of the better controlled, more proximal muscles on the hemiplegic and noninvolved

Fig. 3 The graph shows total hip flexor muscle volume with the adductor longus muscle separately and the total knee extensor muscle volume with the rectus femoris muscle separately for the hemiplegic and noninvolved sides. Values are expressed as mean with SD.

Fig. 4 The graph shows the muscle volume and concentric muscle work ratios (hemiplegic side divided by the noninvolved side) for the various muscle groups. The volume ratio correlated with the work ratio for the ankle plantar flexor muscle ($r = 0.403$; $p < 0.05$), the knee extensor muscle ($r = 0.655$; $p < 0.01$), and the adductor muscle ($r = 0.578$; $p < 0.05$). Values are expressed as mean with SD.

sides. One would think the more pronounced the involvement is, with a higher Winters classification type, the greater the need for compensatory mechanisms would be. As previously reported by Riad et al. [23] and more recently by McDowell et al. [14], in attempts to classify a population-based sample of children with hemiplegic CP, as many as 38 of 94 (42%) could not be classified according to Winters' original classification system [30]. Although the patients in our study had very mild involvement, we detected compensatory mechanisms; this finding implies a strong, more or less conscious drive toward normality and symmetry in movement pattern.

We conclude anatomic muscle volumes are smaller on the hemiplegic side, especially distally in the lower

extremity. The dynamic assessment with GA clearly recognizes deviations in concentric muscle work even in mild hemiplegic CP, and primary deviations can be distinguished from compensatory mechanisms. Furthermore, our strategy of measuring muscle work in association with gait and making correlations to muscle volume differences can be useful in developing targeted muscle-strengthening programs and helping in preoperative assessments when the goal of the surgery is to improve gait.

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