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Relationship in Children with Unilateral Cerebral Palsy Between Muscle Architecture and Functional Motor Skills

Tek Taraflı Serebral Palsili Çocuklarda Kas Mimarisi ile Fonksiyonel Motor Becerileri Arasındaki İlişki

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ABSTRACT Objective: This study aims at investigating the differences in muscle architectural characteristics in children with unilateral cerebral palsy (UCP) and their relationship with functional motor skills. **Material and Methods:** This study enrolled thirty-six children with UCP and thirty-six healthy controls. Leg muscle architecture was evaluated with ultrasound. Functional motor skills were assessed via the Timed Up and Go Test, the 5 Times Sit and Stand Test (5xSST), the 10m Walk Test, the Dimensions D and E of Gross Motor Function Measure-88 (GMFM-88), and the Pediatric Berg Balance Scale (PBS). **Results:** The thickness of the medial gastrocnemius (Gm), lateral gastrocnemius (Gl), tibialis anterior (Ta), and tibialis posterior muscles were smaller in the affected extremity than in the unaffected extremity in UCP ($p=0.004$, $p=0.02$, $p<0.001$, and $p<0.001$; respectively). Except for the soleus (Sol) muscle, the fascicle lengths of the other muscles of the affected extremity were shorter than those of the unaffected extremity ($p<0.05$). There were significant weak-moderate correlations between 5xSST and Gm and Gl muscles thickness (respectively; $r=-0.38$, $p=0.04$; $r=-0.33$, $p=0.02$), between PBS and Gm muscle pennation angle and Sol muscle fascicle length (respectively; $r=-0.37$, $p=0.03$; $r=-0.37$, $p=0.03$). Additionally, a correlation was observed between GMFM-88-E and Ta muscle pennation angle ($r=0.34$, $p=0.04$). **Conclusion:** The muscle architectural characteristics of the affected side of children with UCP was different from those of the unaffected side and from those of healthy controls. These differences affected the functional skill levels of children with UCP.

Keywords: Cerebral palsy; muscle geometry; pennation angle; ultrasound; fascicle length

ÖZET Amaç: Bu çalışmanın amacı, unilateral serebral palsili [unilateral cerebral palsy (UCP)] çocuklarda kas mimari özelliklerindeki farklılıkları ve bunların fonksiyonel motor becerilerle ilişkisini araştırmaktır. **Gereç ve Yöntemler:** Bu çalışmaya 36 UCP'li ve 36 sağlıklı çocuk dâhil edildi. Bacak kas mimarileri ultrasonografi ile değerlendirildi. Fonksiyonel motor beceriler; Zamanlı Kalk ve Yürü Testi, 5 Tekrarlı Otur Kalk Testi [5 Times Sit and Stand Test (5xSST)], 10 Metre Yürüme Testi, Kaba Motor Fonksiyon Ölçütünün [Gross Motor Function Measure-88 (GMFM-88)] D ve E alt grupları ve Pediatrik Berg Denge Ölçeği [Pediatric Berg Balance Scale (PBS)] ile değerlendirildi. **Bulgular:** UCP'li bireylerde etkilenen ekstremitenin mediyal gastroknemius [medial gastrocnemius (Gm)], lateral gastroknemius [lateral gastrocnemius (Gl)], tibialis anterior (Ta) ve tibialis posterior kaslarının kalınlıkları etkilenmeyen ekstremiteye göre daha inceydi ($p=0.004$, $p=0.02$, $p<0.001$, $p<0.001$; sırasıyla). Etkilenmiş ekstremitenin soleus kası hariç diğer kaslarının fasikül uzunlukları etkilenmemiş ekstremiteye göre daha kısaydı ($p<0.05$). 5xSST ile Gm ve Gl kas kalınlığı arasında (sırasıyla; $r=-0.38$, $p=0.04$; $r=-0.33$, $p=0.02$); PBS ile Gm kası pennasyon açısı ve sol kas fasikül uzunluğu arasında; (sırasıyla; $r=-0.37$, $p=0.03$; $r=-0.37$, $p=0.03$) ve GMFM-88-E ile Ta kası pennasyon açısı arasında zayıf-orta korelasyon vardı ($r=0.34$, $p=0.04$). **Sonuç:** UCP'li çocukların etkilenen tarafının kas mimari özellikleri etkilenmeyen taraftan ve sağlıklı taraftan farklıydı. Bu farklılıklar UCP'li çocukların fonksiyonel beceri düzeylerini etkilemiştir.

Anahtar Kelimeler: Serebral palsi; kas geometrisi; pennat açı; ultrasonografi; fasikül uzunluğu

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Cerebral palsy (CP) is a syndrome in which disorders of muscle tone, locomotion, and functional motor ability may arise due to brain lesions occurring in the early developmental period.[1] Despite the nonprogressive brain lesions, the spasticity that occurs in CP causes significant changes in the structure and architecture of skeletal muscles in time.[2] Children with CP have smaller muscles and more fat with less contractile structure in these muscles. Changes in these affected muscles can result in muscle and joint contractures and a decrease in voluntary muscle force production over time.[3,4]

The arrangement of the fibers in the muscle according to the force generation axis has been defined as the skeletal muscle architecture.[5] Muscles are classified according to whether the muscle fibers are parallel (fusiform) or angled to the force-generating axis (pennate muscles).[6] The number of muscle fibers, the cross-sectional area of the muscle, the number of sarcomeres, the geometry of the muscle fibers, and the connective tissue properties are the most important descriptors of the functions of the pennate muscles. These muscle characteristics adapt to growth and development in parallel with changes in body weight and height.[7] Muscle architecture allows us to understand the importance of the muscle's capacity for excursion and its effect on force production patterns.[6,8] Pennation provides a greater physiological cross-sectional area, resulting in greater force generation ability, while an increase in fascicle length enables faster muscle shortening.[9] Imaging methods including dual-energy X-ray, computed tomography, magnetic resonance imaging (MRI), and ultrasonography enable us to evaluate the response to external stimuli as well as measuring in vivo muscle size and architecture.[3,8] Ultrasonography is an easily accessible, safe, radiation-free, and cost-effective method that can quantitatively evaluate muscle size (length, volume), muscle architecture (thickness, cross-sectional area, fiber length, pennation, echogenicity), and muscle stiffness (elastography) with some software.[4]

Although there are few studies examining the muscle structure of children with CP, the results of these studies are inconsistent.[2,4,10-12] Furthermore, the relationship between these muscle architectural characteristics and functional motor skills has not been fully elucidated.[2] Thus, the primary purpose of the present study was to investigate the presence of ultrasonographic differences between the muscle architectures of the posterolateral [medial gastrocnemius (Gm) and lateral gastrocnemius (Gl) and soleus (Sol)] and anterolateral [tibialis anterior (Ta), tibialis posterior (Tp) and peroneus longus (Pl)] distal leg muscles of Turkish children with CP. The secondary purpose was to investigate the association between muscle architectural characteristics and functional motor skills of children with CP.

MATERIAL AND METHODS

SUBJECTS

Thirty-six participants who were followed up with the diagnosis of unilateral spastic CP (2-13 years) between March 2021 and October 2021 at Mersin University Hospital, Department of Physical Medicine and Rehabilitation were included in the study as the experimental group. The inclusion criteria were: (1) Children with unilateral CP who had gross motor function classification system I-II, (2) who could take the ankle to the neutral position (at 0 degrees) while the knee was in full extension., and (3) who did not have a history of botulinum toxin injection in the last 6 months. Children with CP who had lower extremity surgery, or had injuries, fractures, and other disorders that could affect the lower extremity were excluded. Thirty-six age and sex-matched healthy children without any musculoskeletal, endocrine, neurological, hematological, and oncological diseases and who applied to the Pediatric Department of Mersin University Faculty of Medicine were included in the control group. Written informed consent was obtained from parents and/or legal representatives of all individuals. The present study was approved by the Mersin University Clinical Research Ethics Committee (date: April 14, 2021; no: 308) in accordance with the principles of the Declaration of Helsinki.

DESIGN AND PROTOCOL

The present study was designed as a cross-sectional case-control study. Anthropometric, clinical, and ultrasonographic evaluations of the participants were performed in a single visit on the same day.

Age, gender, and dominant extremity of each individual were recorded as demographic data. Height, body weight, extremity lengths, and leg and thigh circumference were measured for anthropometric measurements.

FUNCTIONAL MOVEMENT SKILLS TESTS

The Timed Up and Go Test (TUG), the 5 Times Sit and Stand Test (5xSST), and the 10m Walk Test (10M-WT) were used to evaluate the functional movement skills of the individuals. For the TUG test, a marker was placed on the floor 3 m away from the chair. Each child was seated on a chair and they were asked to stand up out of the chair, walk at their preferred walking speed for 3 m, turn around the marker, walk back to the chair, and then sit down.[13] The time it took for the child to complete this test was recorded with a stopwatch. For the 5xSST, children were asked to sit on a chair without arm support with their arms crossed on the chest. Then, they were asked to stand up and sit down 5 times as fast as they could.[14] A 10 m walking track was set on a long straight corridor for the 10M-WT. The child was asked to walk this 10 m-track at their preferred walking speed, and the time required to walk this distance was recorded.[15] Preferred walking speed of each child was calculated. The total scores from the dimensions D and E of the Gross Motor Function Measure-88 (GMFM-88) were used to evaluate changes in gross motor skills of standing and walking.[16] The Pediatric Berg Balance Scale (PBS) was used to assess balance by an experienced physiotherapist. It is a test with good reliability in school-aged children with mild to moderate motor impairments.[17] Additionally, this test has validity and reliability in Turkish.[18] All children with unilateral CP were referred to an other physiatrist for ultrasonographic examination after functional tests.

ULTRASOUND MEASUREMENTS

All ultrasonographic evaluations were performed by the same physiatrist with a 5-13 MHz linear probe (Logiq P5, GE Medical Systems, Gyeonggi-Do, Korea). Clinical evaluations were performed by a different physiatrist on the same day with US evaluations. Sagittal and coronal cross-sectional images of the leg muscles were recorded, and muscle thickness, pennation angle, and fascicle length were measured. Each parameter was measured 3 times and the mean of these 3 measurements were recorded to minimize the error rate. Bilateral lower extremities of the children with unilateral CP and the dominant lower extremities of the healthy controls were evaluated. Ultrasonographic examination for the Ta, Tp, and Pl muscles was performed with the ankle at 0 degrees, the knee in full extension, and while they were on the bed in the supine position. The assessment of the Gm, Gl, and Sol muscles was performed while the participants were lying on the bed in the prone position and their feet hanging over side of the examination table, with the ankle at 0 degrees and the knee in full extension. The probe was placed vertically on the muscles using plenty of gel and without applying excessive pressure on the muscle. The Gm, Gl, and Sol in the posterior leg region, the Ta and Tp in the anterior leg region, and the Pl in the lateral leg region were measured using US. Ultrasonographic measurement areas of the muscles are described in Figure 1. In line with the recommendations of a previous study, muscle thickness was measured as the distance between the superficial and deep aponeuroses at proximal and distal of the ultrasound image, the fascicle length was measured as the longest visible fiber length between the superficial and deep aponeuroses, and the pennation angle was measured as the angle made by the fascicles with the deep aponeurosis (Figure 2).[2] Muscle thickness (proximal thickness+distal thickness)/2), fascicle length (longest visible fiber length+proximal muscle thickness/sinθ), and pennation angle (the angle made by the fascicle length and the line extending along the deep aponeurosis) were measured.[2] Continuous tracking technique was used at the localization shown in Figure 1 to measure the cross sectional area (CSA) of Tp (Figure 2). The measurements were performed by a physiatrist with 10 years of experience about musculoskeletal ultrasonography.[19]

STATISTICAL ANALYSIS

Analyses were performed using the IBM SPSS Statistics, version 21.0. (Armonk, NY: IBM Corp., USA) program. Normality control of continuous variables was performed with the Shapiro-Wilk test. The linear

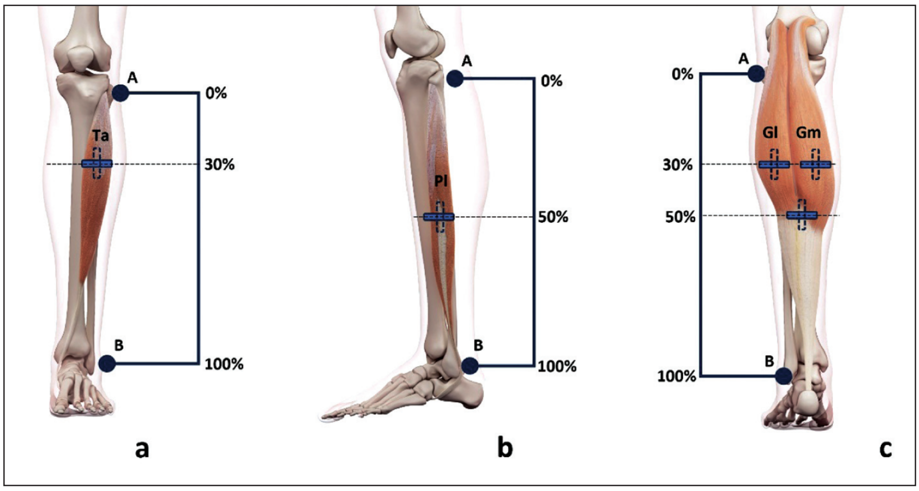

FIGURE 1: Illustration depicting the measurement sites for the skeletal muscle architectural characteristics.
30% of the leg length from the anterior side, measured from the head of the fibula to the lateral malleolus, was used for the Ta and Tp Muscle **(a)**. 50% of the leg length from the lateral side, measured from the head of the fibula to the, was used for the Pl Muscle **(b)**. 30% (for Gm, Gl muscles) and 50% (for Sol muscles) of the leg length from the posterior side, measured from the head of the fibula to the lateral malleolus, was used **(c).**
A: Fibular head; B: Lateral malleolus; Gm: Gastrocnemius medialis; Gl: Gastrocnemius lateralis; Sol: Soleus; Ta: Tibialis anterior; Tp: Tibialis posterior; Pl: Peroneous longus.

relationship between the two continuous variables was evaluated with the Pearson or Spearman Rho coefficient. In the mean/median comparison between independent groups, Student's t test, the Mann-Whitney U test, one-way analysis of variance, and the Kruskal-Wallis tests were applied depending on group size. Chi-square and Fisher exact tests were used in the analysis of categorical variables.

In the reference study, the mean pennate angle of the Gm muscle was reported to be 28.2±3.6 in children with CP, and 25.9±3.2 in children in the control group.[20] According to these values, it was planned to include 36 children in each group and a total of 72 children with 80% power, 5% Type I error, and an effect size of 0.68. The calculation was made using the G*Power 3.1.9.4 program (written by Franz Faul,Universität Kiel, Germany).

RESULTS

DEMOGRAPHIC AND FUNCTIONAL MOVEMENT SKILLS

Individuals' demographic and clinical characteristics are shown in Table 1. There were no statistically significant differences between children with CP and healthy controls in terms of age, gender, and body mass index (BMI) ($p>0.05$). Leg and calf circumference (both dominant and non-dominant) of children with CP are statistically smaller compared to healthy children ($p=0.008$, and $p=0.002$, respectively). Children with CP had longer TUG duration (median values: 9.96 and 7.09, $p<0.001$) and 5xSST duration (median values: 9.37 and 6.9, $p<0.001$). Similarly, children with CP had statistically significantly slower walking speeds (1.03±0.19 and 1.17±0.2, $p=0.002$). In addition, the PBS score of healthy controls were higher than that of children with CP (median values: 56 and 54, $p=0.001$).

COMPARISON OF MUSCLE ARCHITECTURE CHARACTERISTICS

Muscle architecture characteristics are shown in Table 2. There was a statistical difference between the affected and unaffected lower extremities of children with unilateral CP in terms of the thickness of the Gm, Gl, Ta, and Tp muscles ($p=0.004$, $p=0.02$, $p<0.001$, $p<0.001$; respectively). There was no statistical difference between the extremities of the children with CP in terms of the thickness of the Sol and Pl muscles ($p>0.05$). There was a statistically significant difference between the unaffected side of children with CP and healthy controls only in terms of the thickness of the Gl and Ta muscles ($p=0.02$, $p=0.007$; respectively).

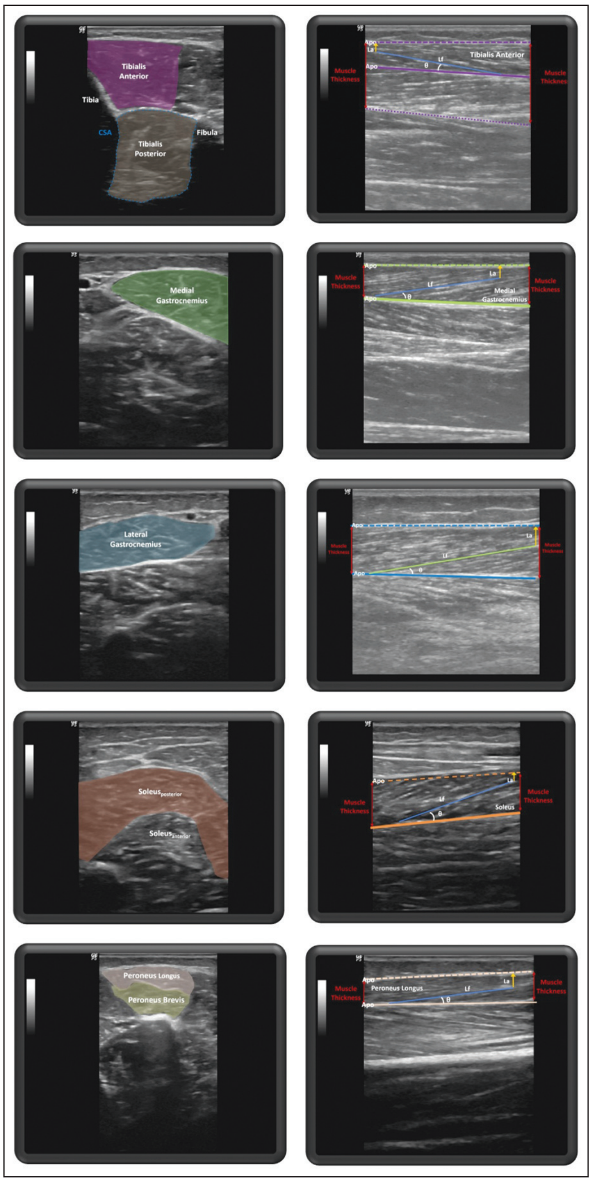

FIGURE 2: Ultrasound images of muscles measured at rest.

Apo: Aponeurosis; CSA: Cross sectional area; MT1: Proximal muscle thickness; MT2: Distal muscle thickness; Lf: Longest fiber length in the visible section by ultrasound; La: Shows the distance from the fiber distal end point to the superficial aponeurosis. The pennation angle was measured (θ) as the angle between the fascicle (green line) and its deep aponeurosis (blue line).

The muscle thickness was measured between the superficial aponeurosis and the deep aponeurosis (blue dashed line) for proximal and distal side. The muscle thickness (MT1+MT2)/2) and the fascicle length (Lf+La/sinθ) were calculated.

TABLE 1: Demographic, anthropometric, and functional movement skills.

	Healthy Controls (n=37)	Cerebral Palsy (n=36)	p value
Gender (n/%)			
Male	17/45.9	20/55.6	0.48
Female	20/54.1	16/44.4	
Age (month)	83 (38-156)	81 (47-144)	0.78
Weight (kg)	22.9 (16-56.4)	20 (12.3-54.3)	0.21
Height (m)^b	1.24±0.16	1.24±0.14	0.72
BMI (kg/m^2)^b	15.4 (12.21-21.58)	14.93 (11.07-29.29)	0.12
Leg length			
Dominant	59 (49-85)	57 (44.5-82)*	0.09
Non dominant	59 (49-85)	56.75 (45-84)	0.06
Thigh circumference			
Dominant	35 (29-47.5)	31.5 (17-45)	0.008
Non dominant	35 (28-47.5)	31 (16.5-43.5)	0.002
Calf circumference			
Dominant	25 (20.5-34)	23 (19-37)	**0.03**
Non dominant	25 (20.5-34)	23 (18-39)	**0.007**
Dominant side			
Right	35/94.6	22/61.1	**0.001**
Left	2/5.4	14/38.9	
Affected side			
Right	-	14/38.9	-
Left		22/61.1	
TUG (s)	7.09 (5.10-11.33)	9.96 (6.45-18.62)	**<0.001**
5xSST (s)	6.9 (4.53-12.84)	9.37 (5.21-23.23)	**<0.001**
Walking speed (m/sec)	1.17±0.2	1.03±0.19	**0.002**
PBS	56 (55-56)	54 (45-56)	**<0.001**

Results were shown as the mean±standard deviation or the median (minimum-maximum) according to normality distribution; BMI: Body mass index; TUG: Time up to go; 5xSST: Five times sit and stand-up test; PBS: Pediatric balance scale.

Pennation angles of all examined muscles in the affected extremities of children with unilateral CP were higher than those of the unaffected extremity muscles, and this difference was statistically significant for the Gl, Sol, and Pl muscles (p=0.04, p=0.04 p<0.001; respectively). Pennation angles of Gm, Gl and Ta muscles were statistically different between the unaffected extremity of children with CP and healthy controls (p<0.001, p=0.005, p=0.006; respectively).

In addition, there was a difference between the affected and unaffected extremities of the children with CP in terms of the CSA of the Tp muscle (p<0.001), but no difference was found between the groups (p>0.05).

CORRELATIONS BETWEEN MUSCLE ARCHITECTURAL AND CLINICAL CHARACTERISTICS

Correlations between muscle architectural and clinical characteristics are shown in Figure 3.There was a

TABLE 2: Muscle architectural characteristics of children with cerebral palsy and healthy controls.

Variables	Groups	Median (Minimum-maximum)	X̅±SD
Muscle thickness (mm)			
Gm	Affected side	9.6* (6.3-13.6)	8.95±1.69
	Unaffected side	10.05 (7.2-14.15)	10.33±1.77
	Dom control	10.5 (7.7-16.2)	10.53±1.85
Gl	Affected side	7.33* (5.00-14.3)	7.55±1.77
	Unaffected side	7.75† (5.2-13.30)	8.02±1.58
	Dom control	8.7• (6.5-14.5)	8.92±1.8
Sol	Affected side	8.85 (5.7-12.2)	8.86±1.39
	Unaffected side	9.25 (6.8-12.3)	9.32±1.43
	Dom control	9.2 (5.7-16.2)	9.52±2.33
Ta	Affected side	11.95* (10-19.7)	12.48±2.2
	Unaffected side	13.95† (8.5-20.8)	14.66±2.53
	Dom control	15.7• (7.6-25.4)	15.93±2.76
Tp	Affected side	13.15* (9-19.5)	14.49±2.82
	Unaffected side	14.75 (7.6-19.8)	14.47±2.78
	Dom control	13.9 (10.7-25.60)	14.69±3.45
Pl	Affected side	3.1 (.3-6.4)	3.27±1.04
	Unaffected side	3.05 (1.5-6.6)	3.22±1.1
	Dom control	3.4 (1.8-7.8)	3.66±1.3
Pennation angles (°)			
Gm	Affected side	13.25* (8.4-17.5)	13.09±2.08
	Unaffected side	11.75† (7.4-16.7)	12.06±2.18
	Dom control	14.6• (10.9-20.7)	14.75±2.40
Gl	Affected side	9.3 (6.8-14.2)	9.43±1.78
	Unaffected side	8.95† (6.1-13.6)	9.30±1.96
	Dom control	10.5• (6-16.4)	10.79±2.39
Sol	Affected side	15.8* (8.2-26.9)	15.6±4.14
	Unaffected side	14.25 (9.2-23.7)	14.4±3.21
	Dom control	14.3 (7.9-29.4)	16.09±5.34
Ta	Affected side	7.7 (5.6-11.4)	7.95±1.49
	Unaffected side	7.6† (4.6-11.1)	7.64±1.22
	Dom control	8.2• (6.4-11.4)	8.43±1.18
Tp	Affected side	6.75* (3.2-9.6)	6.6±1.6
	Unaffected side	5.9 (3.9-8.4)	5.94±1.24
	Dom control	6.5 (3.7-10.2)	6.5±1.38
Fascicle length (mm)			
Gm	Affected side	45.22* (27.51-65.05)	44.65±10.29
	Unaffected side	48.55† (33.47-69.86)	49.48±8.69
	Dom control	41.6• (27.82-59.6)	42.58±8.59
Gl	Affected side	46.2* (31.7-89.13)	48.25±13.61
	Unaffected side	52.21 (35-91.03)	52.79±11.6
	Dom control	47.55 (32.86-73.1)	49.19±11.38
Sol	Affected side	31.74 (14.7-55.48)	32.18±9.64
	Unaffected side	33.9 (22.6-64.82)	36±9.74
	Dom control	31.6 (18-52.18)	31.97±8.11
Ta	Affected side	37.39* (22.32-56.85)	37.57±7.7
	Unaffected side	46.59 (32.94-68.27)	47.94±8.55
	Dom control	46.19 (25.73-63.29)	45.76±9.37
Pl	Affected side	30.35* (14.46-55.28)	30.84±8.46
	Unaffected side	32.62 (20.3-53.4)	33.58±8.28
	Dom control	33.51 (15.73-57.7)	34.94±9.94
CSA (cm^2)			
Tp	Affected side	1.9* (0.86-3.65)	2.04±0.72
	Unaffected side	2.29 (0.79-4.42)	2.3±0.72
	Dom control	2.25 (1-4.09	2.27±0.73

*Shows difference between affected side and unaffected side extremities in cerebral palsy (CP) group; †Shows difference between unaffected side of CP and dominant side (Dom) of control group; •Shows difference between affected side of CP and Dom of control group; SD: Standard deviation; Gm: Medial gastrocnemius; Gl: Lateral gastrocnemius; Sol: Soleus; Ta: Tibialis anterior; Tp: Tibialis posterior; Pl: Peroneus longus; CSA: Cross sectional area.

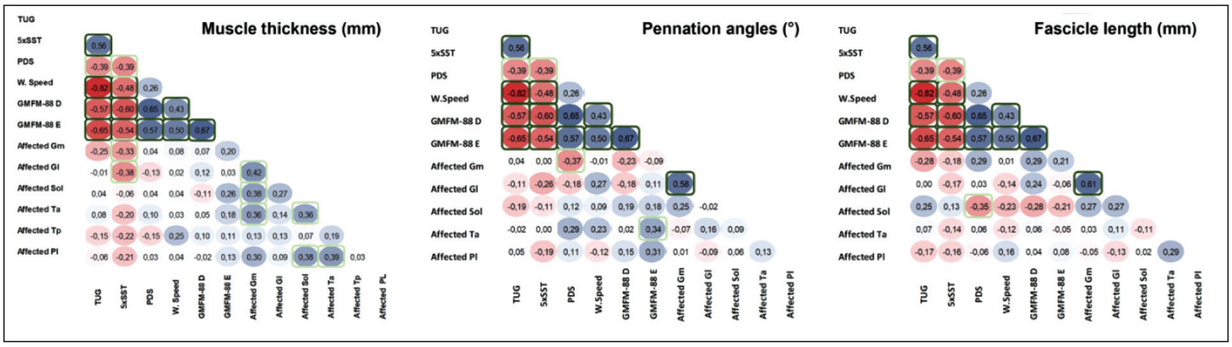

FIGURE 3: Correlations between muscle architectural and clinical characteristics.

TUG: Timed Up and Go Test; 5xSST: 5 Times Sit and Stand Test; PBS: Pediatric Berg Balance Scale; GMFM-88: Gross Motor Function Measure-88; Gm: Medial gastrocnemius; Gl: Lateral gastrocnemius; Sol: Soleus; Ta: Tibialis anterior; Tp: Tibialis posterior; Pl: Peroneus longus.

Blue color indicates positive correlations and red color indicates negative correlations. The stronger the correlation, the darker the colors. Dark green rectangular frame $p<0.05$; A light green rectangular frame indicates $p<0.01$. No rectangular frame indicates $p>0.05$.

statistically weak-moderate negative correlation between the thickness of the affected side Gm and GL muscles and the 5xSST scores (respectively; r=-0.38, p=0.04; r=-0.33, p=0.02). No statistically significant correlation was found between the muscle thickness of the affected side and the TUG, PBS, walking speed, GMFM-88 D and E scores of the children with CP ($p>0.05$).

There was a statistically weak negative correlation between the pennate angle of the affected side Gm muscle and the PBS scores (r=-0.37, p=0.03). There was a statistically weak positive correlation between the pennate angle of the affected side Ta muscle and the GMFM-88-E scores (r=0.34, p=0.04).

There was a statistically significant weak negative correlation between the affected side Sol muscle fascicle length of the children with CP and the PBS scores (r=0.35, p=0.04).

DISCUSSION

We demonstrated that there were differences between functional motor skills and muscle architecture of children with unilateral CP and healthy children. In fact, it was observed that the muscle architectural parameters of individuals with CP were effective on the motor skills of these individuals. To the best of our knowledge, this is the first study comparing distal leg agonist and antagonist muscles of Turkish children with unilateral CP and their healthy counterpart. The muscle architectural characteristics and motor function skills of healthy children and children with CP were investigated, and also the relationship between the affected extremities and motor functions of individuals with CP was investigated in this study.

Skeletal muscles can adapt by reshaping against positive and negative stimuli such as exercise, inactivity, and spasticity.[2] CP is a disease associated with muscle weakness and hypertonicity.[3] The reduction in muscle tissue thickness and fascicle length may have a bidirectional relationship with muscle weakness. It has been shown in the literature that muscle thickness and fascicle length decrease due to disuse and immobilization. On the other hand, it has been reported that children with CP have smaller muscles and fascicle length, resulting in loss of strength and decreased physical activity.[2,21] Consistent with this information, all examined muscles in the present study were thinner on the affected side compared to the unaffected side and those of healthy controls, but the thinness of the Gm, Gl, Ta, and Tp muscles was statistically significant within the group. The Gl and Ta muscles were significantly thinner in the unaffected side of children with unilateral CP than the dominant side of healthy children (10.9% and 11.2%, respectively). In the literature, there are some studies examining the gastrocnemius muscle volume of children with CP and their healthy peers. They reported a volume difference of 22%-57% for the gastrocnemius muscle.[4] The thickness of the gastrocnemius and foot dorsiflexor muscles was reported to be approximately 20% smaller.[3] Park et al. reported that the Gm muscle thickness of the paretic extremity was thinner than the non-paretic extremity and healthy peers in their study, in which they evaluated the lower extremities of children with unilateral CP and their healthy peers. They also stated that Gl thickness did not differ in the affected and unaffected side of individuals with unilateral CP while the Sol muscle thickness in the paretic extremity was statistically thinner than that of healthy controls.[22] The present results were similar for the thickness of the Gm muscle, but different for the thickness of the GI and Sol muscles. There are many methodological differences in studies, such as the method of evaluation of muscle volume (various ultrasound modes, MRI, etc.), the variation in the measurement area of the same muscle, the angle of other joints, and the children population (CP type, ambulation level, age, etc.). For example, the present study included older and younger children (5-10 years and 2-13 years), although the study by Park et al. and the present study had similar inclusion and exclusion criteria and mean age.[22] In addition, Park et al. used the mean muscle thickness of both extremities in healthy children. Barber et al. reported significant positive correlations between Gm muscle volume, muscle length, age, and BMI in both children with spastic CP and healthy children.[4] In addition, Maurits et al. reported a correlation between age and muscle thickness measured by ultrasound.[23] The difference in muscle thickness depends on the severity and type of CP.[3] The knowledge that ambulatory children with CP also have lower motor skills scores than their healthy peers has been confirmed by the present results.[24] We also demonstrated that thickness of the Gm and GI muscles in the affected extremity of children with CP was related with the 5xSST results. As the muscle thickness decreased, the test duration of the children with CP increased. This finding objectively revealed that muscle thickness can provide information about functional skills.

Pennate muscles usually have a larger physiological cross-sectional area because they contain more packed fibers at a given muscle length. Thus, they make it possible to generate larger forces. For example, a 30° pennation angle transmits 86% of the muscle's contraction force to the tendon (30° cosine is 0.86). As the fascicle length increases, the rate of contraction of the muscle also increases.[9] All muscles analyzed in the affected extremity had greater pennation angles than those of the unaffected side, although only a few were statistically significant (the Gm, Sol, and Pl muscles). There is inconsistency in the results of studies examining the effect of CP on children's muscle architecture. Although most of the studies have focused on the Gm muscle, there are studies reporting that the pennation angles of children with CP are similar, larger, or smaller than those of healthy children.[11,22,25-27] Since there is a high correlation between muscle thickness and pennation angle in healthy individuals, this outcome is expected in individuals with CP. However, it was reported that this correlation was weaker and not statistically significant for the paretic extremity.[28] Various factors such as atrophy and spasticity may affect the pennation angle and fascicle length of the paretic extremity in individuals with CP. It has been argued that the effect of spasticity on the aponeurosis of the fascicles, such as shortening of the fascicles that occurs in a pennate muscle during voluntary contraction, may increase the pennate angle and shorten the fascicle length.[28] Although it is known that the angles of different joints have an effect on muscle fascicle length and angle, changes in other agonist and antagonist muscles may also have an effect on fascicle length and angle. Statistically significant correlations between the thickness of the affected side Gm muscle and the Gl, Sol, and Ta muscles in the present study. There was also a moderate correlation were detected between affected side Gm and Gl muscles for pennation angle and fascicle length. On the other hand, the presence or absence of muscle architecture differences in individuals with CP may also be muscle dependent.[3] The muscles of the individuals with unilateral CP examined on the affected side (except for the Sol) had statistically shorter fascicle lengths than those of the unaffected side. The fascicle length of the affected side Sol muscle was shorter, but the difference was not statistically significant. On the other hand, although the fascicle lengths of the muscles in the unaffected extremities of the individuals with CP (except the Pl muscle) were longer than those of the healthy controls, this length difference was statistically significant only for the Gm muscle. This finding suggests that there are changes in the architectural characteristics of the unaffected extremity for compensation.

In addition to muscle thickness, muscle length and muscle volume, pennate angle, and fascicle length have a strong relationship with power and muscle strength.[9] There are some studies examining the relationships between pennate angles, fascicle lengths, various body structures, and functions (muscle strength, step length, ground reaction force), and activity levels (walking speed, GMFM-88, TUG) of individuals with CP. Non-significant or weak correlations constitute the majority of the literature.[12] Chen et al. reported that there was a statistically significant positive correlation between the fascicle length of the Gl and GMFM-88 scores of individuals with CP.[2] Bland et al. found a negative relationship between the pennation angle of the Ta muscle and walking speed.[29] In the present study, there were positive correlations between the pennation angle of the affected extremity Ta muscle and the GMFM-88 E scores, and weak-to-moderate negative correlations between the pennation angle of the affected side Gl muscle and the PBS scores. The architectural characteristics of different muscles can have relationships in different directions at various levels. However, as there is no clear consensus about these relationships, they remain unclear and are worthy of further investigation.

The present study had some limitations. First, the lower extremity spasticity levels of the children participating in the study could not be standardized. Second, measurements were made only when the knee was in full extension and the ankle was at 0 degrees. Measurements at different angles could provide more information about muscle architecture. Third, the distal lower extremity muscles of children with CP were examined, and the possible effects of proximal muscles on these muscles could not be evaluated.

CONCLUSION

Our study showed that muscle thicknesses, pennation angles, and fascicle lengths were different between the affected and unaffected extremities of individuals with unilateral CP as well as those of the extremities of healthy individuals. It has been observed that the distal lower extremity muscle thickness, pennate angles, and fascicle lengths of CP children are related to parameters such as PBS, 5xSST, and GMFM-88-E. This demonstrates how muscle architectural structure influences the functional levels of children with CP.

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