CORRELATION BETWEEN MUSCLE FASCICLE LENGTH, SPASTICITY AND FUNCTIONAL ABILITIES

Momen ELsaied ELsagher[1*], Amira Mohamed ElTohamy[2], Abdallah Abbas[3], Ahmed S. Awad[2,4]

Article History: Received: 10.04.2023 **Revised:** 06.05.2023 **Accepted:** 11.05.2023

Abstract

Background: Upper motor neuron lesions are characterized by spasticity, which impairs motor abilities necessary for daily activities and can also result in structural alterations in the muscle which can be detected by ultrasonography. The study's aim was to dictate the effects of spasticity in children with cerebral palsy (CP) on functional abilities and the length of the quadriceps fascicle (QFL).

Methods: The study's inclusion was constrained to 100 CP children, 50 of them were spastic and the other 50 were normal. Their ages were from four and six years, and they were able to stand with holding on. The functional abilities were evaluated using the Gross Motor Function Measure-88 (GMFM-88), The degree of spasticity was evaluated using the Modified Ashworth Scale (MAS) and QFL was assessed by Ultrasonography (US).

Results: There was a substantial variation in (QFL) comparing the spastic and normal groups ($p > 0.05$), as well as a significant association between spasticity and (QFL) ($p > 0.05$) and between spasticity and functional skills ($p > 0.05$).

Conclusion: In children with spastic CP, spasticity has a considerable impact on (QFL) and functional abilities.

Keywords: Spasticity, fascicle length, Ultrasonography, Functional abilities, spastic children.

[1]Department of Physical Therapy for Pediatrics, Faculty of Physical Therapy, Nahda University, Beni Sueif, Egypt.
[2]Department of Physical therapy for Pediatrics, Faculty of Physical Therapy, Cairo University, Egypt.
[3]Department of diagnostic radiology, Faculty of Medicine, Fayoum University, Egypt.
[4]Department of Physical therapy for Pediatrics, Faculty of Physical Therapy, October 6 University, Egypt.
[*]Corresponding Email: momen.elsaied@nub.edu.eg

1. INTRODUCTION

Spasticity is defined as an aberrant uncontrollable contraction of muscles caused by a speed-dependent rise in resistance to passive muscular stretching, or paralysis of the upper motor neurons [1,2]. Children with spasticity due to cerebral palsy exhibit rigidity, hyperactive reflexes, and increased muscle tone. Contractures, which can form as a result of increased muscle tone, can limit the range of motion in the joints [3].The most prevalent cause of spasticity is brain, spinal cord and stretch reflex affection or disturbance. Spasticity affects two-thirds of all children with CP [4]. Spasticity can affect any muscle in the body, though CP has some characteristic patterns: Flexion at the elbow, wrist, and fingers is the outcome on the upper limbs. Hip flexion, adduction or "scissoring," knee flexion, equinovarus foot posture, and big toe hyperextension are examples of lower limb impacts. Spasticity can occur in smaller muscles as well, such as the tongue and face muscles [5]. According to the MAS, which categorizes spasticity according to resistance to passive movement, was generally recognized as having excellent validity and reliability for detecting muscle tone abnormality in CP [6]. Spasticity management in CP entails interdisciplinary intervention aimed at increasing functionality, maintaining wellness, and enhancing both the children's and the carers' quality of life. Examples of such therapies include Oral pharmaceuticals, endoscopic medications, physiotherapy, occupational therapy, orthoses, surgical procedures, and pharmacological agents like botulinum toxin are only a few examples [5]. The contractile component of skeletal muscle tissue can change its internal architecture in response to external stimuli. Characterizing muscle structure can help in understanding the numerous mechanisms involved in muscle injury, ageing, and neuromuscular illnesses because muscle structure is directly linked to activity [7]. Muscle structure is a fundamental predictor of performance. Regarding the axis of force generation, the interior configuration of muscle fibers through a muscle is referred to as muscular architecture [8]. Ultrasound has been employed in determining the severity of disease and pathology of skeletal muscles [4]. Sonography, also referred to as US scanning, is a form of imaging that uses reflected high-frequency ultrasonic sound waves to scan cartilage, muscles, bone surfaces, and fluid-containing tissues [9]. Muscle architecture measurements include muscle thickness, fascicle angle, fascicle length and areas of physiological and anatomical cross-section [10]. The distance between the sites where a superficial aponeurosis and a fascicle cross and meet with the deep aponeurosis was defined as fascicle length (FL) [8]. The earliest scanning technology to fully assess human muscle mass in living beings was ultrasound [11]. For children with cerebral palsy, the Gross Motor Function Measure (GMFM) is a frequently used, criterion-referenced clinical observation tool that was created and validated. It has high reliability and the potential to detect important alterations in children with CP's gross motor function [12]. The evaluation of FL changes in relation to changing spasticity offers insight into how spasticity affects FL, and their relations to functional skills can help in the development of an efficient rehabilitation program.

2. METHODS

- **Study design**

This study was a cross-sectional study.

- **Subjects**

The ethics review committee of the Faculty of Physical Therapy, Cairo University NO (**P.T.REC/012/003284**) approved this study during 2020, and parents signed a consent form approving their child's participation and publication of results. A total of 100 CP children of both sexes were separated into two groups: spastic (50 children) and normal (50 children). They were originally tested to determine inclusion and exclusion criteria. The following were the inclusion criteria: Both sexes' ages ranged from four to six years. According to the MAS, their degree of spasticity ranged from 1 to 3 [13]. The Gross Motor Function Classification Scale (GMFCS) was utilized to evaluate motor function [22], only children in level III were taken into account. Children were competent in following instructions during the testing process. Children with deformities of the knee joint, those without spasticity or with lower limb flexor spasticity, as well as those using antiepileptic medications or the drug peak action occurred during the testing for spasticity, were eliminated.

- **Procedures:**

When the investigation first began, parents provided details about their child, such as their child's name, age, and address. An overview of the research and how it can benefit their children was cleared to the parents.

- **Evaluation of spasticity**

Evaluation was done on the level of spasticity using MAS. in all children in the spastic group using the following instructions:

• Lay the patient on their backs.

• Start with the knee extended and advance to the end of knee flexion in one instant (count one thousand one).

• Next, based on MAS classification, the child was given a score [13].

- **Measurement of fascicle length**

Using GE LOGIQ P6 ultrasonography equipment with a frequency of 7.5 MHz, the muscle fascicle length of the quadriceps muscles was measured from lying on back posture while knee extended and the hip in the mid position [14]. 3/5 of the way from the upper patellar border to the anterior superior iliac spine, on the superior surface of the thigh, exactly parallel to the thigh's long axis, the transducer probe was placed. By linking the points where the superficial aponeurosis and fascicle and the deep aponeurosis and fascicle cross, the length of the fascicle was determined. **Figure (1).**

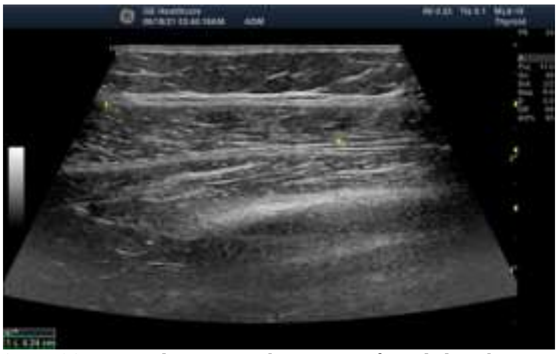

Figure (1): Using ultrasonography to assess fascicle length.

- **Evaluation of functional ability**

Children's motor function was evaluated using the GMFM-88, a popular test for children with cerebral palsy. The 88 items are used in the test, which are separated into 5 categories: lying down and rolling, sitting, crawling on hands and knees, standing, and walking, running, and jumping [15].

In this study, the researcher followed the duties of the standing domain (standing holding on) in GMFM-88, the investigator first had the child stand up while using one or both hands to grasp a stand bar, depending on the child's abilities. The researcher then calculated the percentage of completed tasks by dividing the number of task completion by the total number of tasks in the standing domain, multiplying the result by 100, and recording the result on an excel sheet.

- **Estimation of the sample size**

With a power of 95% and a type I error of 5%, the F-test (MANOVA) was used to determine the sample size. The primary outcome (FL) from a 15-subject pilot research was used to calculate the effect size (0.706). In the EAC group, a minimum sample size of 45 patients was used; this number was then raised by 10% to account for dropouts. Version 3.1.9.2 of G* Power (*Franz Faul, University of Kiel, Germany*) utilized to calculate the results.

STATISTICAL ANALYSIS:

Using the Shapiro-Wilk test, all of the data's distribution was found to be normal. It was done using the Chi square (X2) test to determine how the groups differed in terms of sex and the affected side, and an independent t test was utilized to evaluate demographic data. Independent T test was applied to compare the length of the muscle fascicles in the normal and spastic groups, and Person correlation test was applied to look at the relation between the impact of spasticity on FL. In the spastic group, GMFM. Version 23 of SPSS was used for all analyses (IBM Corp., New York, USA).

3. RESULTS

- **Demographic data:**

Independent T test reported that 100 patients in two groups were matched regarding age, BMI, as well as Chi square analysis revealed no sex differences across groups. **(Table 1).**

Table (1): Demographic data

Variables	Normal Group M Mean ± SD	Spastic Group M Mean ± SD	T value	p-value
Age: (years)	4.60±0.72	4.56±6.1.19	0.202	0.841*
BMI: (kg/cm^2)	23.58±1.34	23.36±1.47	0.799	0.426*
Sex distribution				
Males	30(40%)	27 (30%)	X^2=0.367	0.544*
Females	20 (60%)	13 (70%)		

*: no significance difference; SD: standard deviation; p-value: significance level; X^2; chi square test.

Independent T test revealed that there was a statistically significant difference between value of Muscle fascicle length at confidence interval 99% for two groups in favor of normal group with mean value 42.79, SD 4.32but spastic group with mean value 31.92, SD 4.14 with T value = 12.82 and p value = 0.000 which it less than significant level ($p<0.05$) as shown in **Table (2).**

Person correlation test was performed in spastic group and revealed that:

1-There is a significant correlation between Muscle fascicle length and Functional Abilities (GMFM) at confidence interval 99%, this correlation is positive and moderate with value 0.559.

2-There is a significant correlation between Muscle fascicle length and Spasticity (MAS) at confidence interval 99%, this correlation is negative and strong with value -0.642.

3-There is a significant correlation between Functional Abilities (GMFM) and Spasticity (MAS) at confidence interval 99%, this correlation is negative and very strong with value -0.927.

Table (2): Comparison between Muscle fascicle length values of the two studied groups (normal and spastic).

Variables	Normal Group Mean ± SD	Spastic Group Mean ± SD	T value	p-value
FL	42.79±4.32	31.92±4.14	12.82	0.0001**

**: significance difference; SD: standard deviation; p-value: significance level

Table (3): The correlation between MAS, FL and GMFM

		Muscle fascicle length (FL)	Spasticity (MAS)	Functional Abilities (GMFM)
FL	**Pearson Correlation**	1	-.642**	.559**
	Sig. (2-tailed)		.000	.000
	N	50	50	50
MAS	**Pearson Correlation**	-.642**	1	-.927**
	Sig. (2-tailed)	.000		.000
	N	50	50	50
GMFM	**Pearson Correlation**	.559**	-.927**	1
	Sig. (2-tailed)	.000	.000	
	N	50	50	50
**. Correlation is significant at the 0.01 level (2-tailed).				

The impact between variables was tested using coefficient of Model and Goodness of fit.
H1: There is a negative impact for Spasticity (MAS) on Muscle fascicle length.
Independent Variables: Spasticity (MAS)
Dependent variables: Muscle fascicle length

Table (4): Coefficient of Model and Goodness of fit

	Unstandardized Coefficients		Standardized Coefficients	t	P value
	B	Std. Error	Beta		
(Constant)	38.601	1.238		31.191	0.000
Spasticity (MAS)	-3.212	0.553	-0.642	-5.803	0.000
Dependent Variable: Muscle fascicle length					
R	.642**				
R Square	0.412				
Adjusted R Square	0.400				
Df	1 / 48				
F	33.680				
p value	.000				

From the above table it is clear that the coefficient of determination (R square) equal to .412, and this indicates that the independent variables (Spasticity (MAS) explain 41.2% of any change in the Muscle fascicle length. In addition that the regression model statistically significant when the F test equal 33.680 at confidence interval 99% (p value 0.000 < 0.01).

Regression Equation.
y= b_0+ b_1 X_1+b_2 X_2+ …+e
When: -
y : Dependent variable.
X_1: First independent variable.
X_2: Second independent variable.
E : error.

Muscle fascicle length = 38.601 - 3.212(Spasticity (MAS))
From the equation, it is clear that if Spasticity (MAS) increased by one unit, the Muscle fascicle length will decrease by 3.21 units. So, there is a negative impact for Spasticity (MAS) on Muscle fascicle length

H2: There is a positive impact for Muscle fascicle length on Functional Abilities (GMFM).
Independent Variables
Muscle fascicle length.
Dependent variables:
Functional Abilities (GMFM)

Table (5): Coefficient of Model and Goodness of fit

	Unstandardized Coefficients		Standardized Coefficients	T	P value
	B	Std. Error	Beta		
(Constant)	0.665	4.706		0.141	0.888
Muscle fascicle length	0.683	0.146	0.559	4.674	0.000
Dependent Variable: Functional Abilities (GMFM)					
R	.559**				
R Square	0.313				
Adjusted R Square	0.298				
Df	1 / 48				
F	21.845				
p value	.000				

From the above table it is clear that the coefficient of determination (R square) equal to .313, and this indicates that the independent variables (Muscle fascicle length) explain 31.3% of any change in the Functional Abilities (GMFM). In addition that the regression model statistically significant when the F test equal 21.845 at confidence interval 99% (p value 0.000 < 0.01).

Regression Equation.
Functional Abilities (GMFM) = 0.665 + 0.683 (Muscle fascicle length)
From the equation, it is clear that if Muscle fascicle length increased by one unit, the Functional Abilities (GMFM) will increase by 0.683 units. So there is a positive impact from Muscle fascicle length on Functional Abilities (GMFM).

H3: There is a negative impact for Spasticity (MAS) on Functional Abilities (GMFM).
Independent Variables
-Spasticity (MAS).
Dependent variables:
-Functional Abilities (GMFM)

Table (6): Coefficient of Model and Goodness of fit

	Unstandardized Coefficients		Standardized Coefficients	T	P value
	B	Std. Error	Beta		
(Constant)	34.271	0.738		46.421	0.000
Spasticity (MAS)	-5.669	0.330	-0.927	-17.169	0.000
b. Dependent Variable: Functional Abilities (GMFM)					
R	.927**				
R Square	0.860				
Adjusted R Square	0.857				
Df	1 / 48				
F	294.789				
p value	.000				

From the above table it is clear that the coefficient of determination (R square) equal to .860, and this indicates that the independent variables (Spasticity (MAS)) explain 86.0% of any change in the Functional Abilities (GMFM). In addition, that the regression model statistically significant when the F test equal 294.789 at confidence interval 99% (p value 0.000 < 0.01).

Regression Equation.
Functional Abilities (GMFM) = 34.271 - 5.669 (Spasticity (MAS))
From the equation, it is clear that if Spasticity (MAS) increased by one unit, the Functional Abilities (GMFM) will decrease by 0.683 units. So there is a negative impact from Spasticity (MAS) on Functional Abilities (GMFM).

4. DISCUSSION

This study's objective was to determine how spasticity affected muscle fascicle length and functional ability in spastic children. The findings of this research demonstrated a significant difference in quadriceps fascicle length between the spastic and normal groups. In the normal group, there was a strong relation between spasticity and quadriceps fascicle length, as well as a strong relation exists between functional ability and spasticity. The quadriceps femoris (two joint) muscle, which extend the knee in the lower limb, is a typical spastic muscle., so it was chosen in this study to use the US to detect the impact of spasticity on fascicle length.
The current study's outcomes are similar to the ones of **Yasser et al** [14], who discovered that, compared to the unaffected side, stroke patients' affected sides exhibited shorter fascicles and thinner muscles. In addition, **Shortland et al. [**16] shown that in a sample of 18 diplegic children, as comparison to children with normal development, adults' gastrocnemius muscle fascicle lengths were shorter in diplegic children than normal children. Furthermore, **Mohagheghi et al** [17] noticed that variations in muscle fascicle length have been documented in healthy persons as a result of disuse, such as bed rest and compelled immobility after a bone fracture. Moreover, **Spector** and **colleagues** [18] found that due to persistent joint malposition and decreased mechanical loading, a decrease in the quantity of serial sarcomeres is associated with human muscular paresis. On the other hand, **Mohagheghi et al** [19] found that despite the fact that they all exhibited shorter fascicle lengths as a group after adjusting the length of the legs, age, mass, and the angle of the joint, the authors indicated that not all children with CP experienced fascicle length shortening. As a result, it is doubtful that one-time or irregular measurements of fascicle length will be diagnostic of CP. According to the study's outcomes, there is a significant correlation between muscle fascicle length and Spasticity (MAS) at 99% confidence interval, and this correlation is negative and strong with value -0.642, indicating that when seeking to determine the degree of muscle spasticity and tracking the efficacy of various treatment modalities, repeated measurements of fascicle length taken over time in a person may be a more acceptable technique. **Barber et al** [20] disagree with this study, between children with spastic CP and children 2 to 5 years old who are generally developing, The length of the muscle fascicles in the gastrocnemius muscle was indistinguishable from one another. Spasticity-related loss of range-of-motion loss leads to reduction of the fascicle length of this muscle, so the muscle cannot extend to its full length. In addition, the spastic muscle may become tighter with time, further reducing the fascicle length even more.
This study's findings on the relationship between spasticity and function are consistent with those of **Tuzson et al** [21], who claimed that spastic threshold velocity for the quadriceps and hamstrings using electromyography during isokinetic testing is

negatively in relation to the GMFM, indicating that higher function is achieved with less spasticity. Also, **Damiano et al** [22] discovered a strong negative correlation between spasticity and the GMFM. Furthermore, **Abel and colleagues** [23] discovered the GMFM-66 and the Ashworth scores for hip flexion and extension, abduction, and knee flexion and extension all had a somewhat negative relationship, nonetheless, there wasn't any meaningful relationship between ankle spasticity and Gross Motor Function. In contrast, **Ross and Enosburg** [24] argued that wasn't a lot to no significant correlation between function and spasticity. By limiting mobility and deteriorating movement smoothness, spasticity can make it difficult for a child to carry out functional activities, which hinders them from properly completing tasks.

The force produced and the muscle fibers' starting length by contraction serves as the foundation for the Frank-Starling relationship. how long the sarcomeres are and the muscle fibers' tension have a predictable connection. There is a perfect distance between sarcomeres where the tension in the muscle fiber is highest and the contractional force is greatest. The tension and power of contraction will be reduced if sarcomeres are located either closer together or further apart than this ideal length [25]. **Merino-Andrés et al.** [26] found that the International Classification of Functioning, Disability, and Health results for the particular domains show an improvement in a number of structural and functional aspects, such as decreased energy expenditure when walking, improved balance, joint ranges, and decreased spasticity. A positive influence on GMFM scores, notably in the GMFM domains for standing, walking, running, and leaping, provides as proof that, for the first time, a systematic review of strength training programs for children and teens with CP resulted in a favorable outcome in the activity domain. Also, improvements in distance reached in a given amount of time were seen, indicating an extension of walking capabilities.

The current study's results agreeing with those of **de Boer et al.** [27], who claimed that skeletal muscles can adjust to a range of stimuli, both good and bad, such as strength training, inactivity, spasticity, and immobility. Research using both human and animal models has demonstrated that muscles contract and shorten their fascicles while inactive or immobile, which may contribute to muscular weakening and imbalance [28]. **Noble et al.** [28] also proposed the possibility that a loss in muscle growth throughout childhood may be the root of the mobility decline found in spastic CP youth and adults. The soleus, gastrocnemius, and tibialis anterior muscles of children with CP also displayed decreased muscle thickness and fascicle length, according to **Chen et al** [29]. These modifications might make it harder for some people to walk and stand. These changes also suggest that children with spastic CP need to have their afflicted muscles strengthened. Spastic muscles are unable to move normally because they are tight or stiff, movement and motor skills are restricted because the muscles are constrictive and challenging to stretch.

A limitation of this study was that because of their fear, some children refused to conduct the US measurement, which changed the measurement's location, and as a result, more measurement trials were conducted to find an appropriate position for measurement.

5. CONCLUSION

Based on the results of the current study, it may be concluded that spasticity negatively affects the fascicle length and functional abilities in spastic children. Also, the positive impact of muscle fascicle length on functional abilities (GMFM) direct the rehabilitation program towards improving the fascicle length of spastic muscles.

Conflict of interest

There are no potential conflicts of interest for the authors to declare.

6. REFERENCES

1. Goldstein E. M. (2001). Spasticity management: an overview. Journal of child neurology, 16(1), 16–23. https://doi.org/10.1177/088307380101600104.
2. Sanger, T. D., Delgado, M. R., Gaebler-Spira, D., Hallett, M., Mink, J. W., & Task Force on Childhood Motor Disorders (2003). Classification and definition of disorders causing hypertonia in childhood. Pediatrics, 111(1), e89–e97.
3. Botte, M. J., Nickel, V. L., & Akeson, W. H. (1988). Spasticity and contracture. Physiologic aspects of formation. Clinical orthopaedics and related research, (233), 7–18.
4. Awaad Y, Rizk T. (2012): Spasticity in children. Journal of Taibah University Medical Sciences; 7(2):53-60.
5. Dimitrijevic L, Colovic II, Spalevic M, Stancovic A, Zlataiiovic D, Cvetcovic B. (2014): Assessment and treatment of spasticity in children with cerebral palsy. Scientific Journal of the Faculty of Medicine; 31(3):163-169.
6. Waninge A, Rook R.A, Dijkhuizen A, Gielen E, van der Schans C.P. (2011): Feasibility, testretest reliability, and interrater reliability of the Modified Ashworth Scale and Modified Tardieu Scale in persons with profound intellectual and multiple disabilities. Res Dev Disabil; 32:613620.
7. Debernard L, Robert L, Charleux F, Bensamoun S.F. (2011): Characterization of muscle architecture in children and adults using magnetic resonance elastography and ultrasound

techniques - Journal of Biomechanics; 44:397-401.

8. Legerlotz K, Smith H.K, Hinge W.A. (2010): Variation and reliability of ultrasonographic quantification of the architecture of the medial gastrocnemius muscle in young children-Journal of Clinical Physiological Function Imaging; 30:198-205.
9. Bakewell, C. J., Olivieri, I., Aydin, S. Z., Dejaco, C., Ikeda, K., Gutierrez, M., Terslev, L., Thiele, R., D'Agostino, M. A., Kaeley, G. S., & OMERACT Ultrasound Task Force (2013). Ultrasound and magnetic resonance imaging in the evaluation of psoriatic dactylitis: status and perspectives. The Journal of rheumatology, 40(12), 1951–1957.
10. Moreau N.G, Simpson K.N, Teefey S.A, Damiano D.L. (2010): Muscle architecture predict maximum strength and is related to activity levels in cerebral palsy. Phy Ther; 90: 1619-1630.
11. Ikai, M., & Fukunaga, T. (1968). Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. Internationale Zeitschrift fur angewandte Physiologie, einschliesslich Arbeitsphysiologie, 26(1), 26–32. https://doi.org/10.1007/BF00696087
12. Rosenbaum P.S., Hanna S., Palisano R., Russell D., Raina P., Wood E., Bartlett D., and Galuppi B., (2002): Prognosis for Gross Motor Function in Cerebral Palsy: Creation of Motor Development Curves. Journal of the American Medical Association 288(11):1357-63.
13. Yang Y, Zhang J, Leng Z, Chen X, Song W (2014): Evaluation of spasticity after stroke by using ultrasound to measure the muscle architecture parameters: a clinical study. Int J Chin Exp Med; 7(9):2712-2717.
14. Yasar E, Kesikburun S, Adigüzel E, Alaca R, Tan A.K. (2014): Assessment of spasticity with sonoelastography in stroke patients. Annuals of physical and rehabilitation medicine; 57(s1):e20
15. Russell D.J, Rosenbaum P.L, Cadman D.T, et aI. (1989): The Gross Motor Function Measure: A means to evaluate the effects of physical therapy. Journal of Developmental Medicine and Child Neurology; 31:341—52.
16. Shortland AP, Fry NR, Eve LC, Gough M. (2004) Changes to medial gastrocnemius architecture after surgical intervention in spastic diplegia. Dev Med Child Neurol 46: 667–673.
17. Mohagheghi AA, Khan T, Meadows TH, Giannikas K, Baltzopoulos V, Maganaris CN. (2007) Differences in gastrocnemius muscle architecture between the paretic and non-paretic legs in children with hemiplegic cerebral palsy. Clin Biomech 22: 718–724.
18. Spector SA, Simard CP, Fournier M, Sternlicht E, Edgerton VR. (1982) Architectural alterations of rat hind-limb skeletal muscles immobilized at different lengths. Exp Neurol 76: 94–110
19. Mohagheghi, A.A. et al. (2008) “in vivogastrocnemius muscle fascicle length in children with and without diplegic cerebral palsy,” Developmental Medicine & Child Neurology, 50(1), pp. 44–50.
20. BARBER, L.E.E. et al. (2011) “Medial gastrocnemius muscle volume and fascicle length in children aged 2 to 5 years with Cerebral Palsy,” Developmental Medicine & Child Neurology, 53(6), pp. 543–548.
21. Tuzson A.E, Granata K.P, Abel M.F. (2003): Spastic velocity threshold constrains functional performance in cerebral palsy. Archives of Physical Medicine and Rehabilitation Journal; 84:1363-8.
22. Damiano D.L, Laws E, Carmines D.V, Abel M.F. (2006): Relationship of spasticity to knee angular velocity and motion during gait in cerebral palsy. Journal of Gait and Posture; 23:1-8.
23. Abel M.F, Damiano D.L, Blanco J.S, et al. (2003): Relationships among musculoskeletal impairments and functional health status in ambulatory cerebral palsy. Journal of Pediatric Orthopedics; 23:535-41.
24. Ross S.A, Engsberg J.R. (2007): Relationships Between Spasticity, Strength, Gait, and the GMFM-66 in Persons With Spastic Diplegia Cerebral Palsy. Archives of Physical Medicine and Rehabilitation Journal; 88:1114-20.
25. Delicce AV, Makaryus AN. Physiology, Frank Starling Law. 2022 Feb 10. In: .StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2022 …….Jan–. PMID: 29262149.
26. Merino-Andrés J, García de Mateos-López A, Damiano DL, Sánchez-Sierra .A. Effect of muscle strength training in children and adolescents with spastic.cerebral palsy: A systematic review and meta-analysis. Clin Rehabil. 2022 …….Jan;36(1):4-14. doi: 10.1177/02692155211040199. Epub 2021 Aug 18.
27. de Boer MD, Maganaris CN, Seynnes OR, Rennie MJ, Narici MV. Time course of muscular, neural and tendinous adaptations to 23 day unilateral lower-limb suspension in young men. J Physiol. 2007; 583: 1079–1091.
28. Noble JJ, Fry N, Lewis AP, Charles-Edwards GD, Keevil SF, Gough M, et al. Bone strength is related to muscle volume in ambulant individuals with bilateral spastic cerebral palsy. Bone. 2014; 66: 251–255.
29. Chen, Y. et al. (2018) “Comparison of calf muscle architecture between Asian children with spastic cerebral palsy and typically developing peers,” PLOS ONE, 13(1).