Relative fascicle excursion effects on dynamic strength generation during gait in children with cerebral palsy

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A B S T R A C T

Evaluation of muscle structure gives us a better understanding of how muscles contribute to force generation which is significantly altered in children with cerebral palsy (CP). While most muscle structure parameters have shown to be significantly correlated to different expressions of strength development in children with CP and typically developing (TD) children, conflicting results are found for muscle fascicle length. Muscle fascicle length determines muscle excursion and velocity, and contrary to what might be expected, correlations of fascicle length to rate of force development have not been found for children with CP. The lack of correlation between muscle fascicle length and rate of force development in children with CP could be due, on the one hand, to the non-optimal joint position adopted for force generation on the isometric strength tests as compared to the position of TD children. On the other hand, the lack of correlation could be due to the erroneous assumption that muscle fascicle length is representative of sarcomere length. Thus, the relationship between muscle architecture parameters reflecting sarcomere length, such as relative fascicle excursions and dynamic power generation, should be assessed. Understanding of the underlying mechanisms of weakness in children with CP is key for individualized prescription and assessment of muscle-targeted interventions. Findings could imply the detection of children operating on the descending limb of the sarcomere length–tension curve, which in turn might be at greater risk of developing crouch gait. Furthermore, relative muscle fascicle excursions could be used as a predictive variable of outcomes related to crouch gait prevention treatments such as strength training.

Introduction

Children with cerebral palsy (CP) can be classified according to motor abnormalities as spastic, dyskinetic, or ataxic, with the most dominant being spastic CP [1]. Children with spastic CP present spasticity, impaired selective motor control, impaired postural control, and muscle weakness as primary problems associated with a central nervous system lesion occurring in the immature brain [2]. In general, strength assessments of children with CP highlight their weakness relative to TD children [3–5]. Muscle weakness has been related to impaired neural control mechanisms, intrinsic muscle mechanics, and altered muscle architecture [6]. Because weakness in children with CP is usually treated at the muscle level, treatment goals and effects should as well be addressed at the muscle [7]. Evaluation of muscle structure gives us a better understanding of how muscles contribute to force generation [8–10] in children with CP, and in turn, to gait ability [4,5] and should therefore be assessed in detail [3,7,11,12].

Muscle growth and regeneration capacity seen in muscles is due to its intrinsic stem cell population, which is reduced in children with CP [7]. Thus, muscle structure has been shown to be significantly altered in children with CP with respect to typically developing (TD) children [3,7,11,12]. More specifically, reduced muscle volume, cross-sectional area, thickness, and belly length have been observed in comparison to TD children [11]. Furthermore, muscle structure has shown to be significantly correlated to muscle strength in TD children [13] and in children with CP [8–10]. Thus, there is a relationship between how the muscle is structured and the capacity to generate muscle force such as maximal isometric strength [8–10], velocity of isometric strength generation [9], and isokinetic strength [10].

Alterations in muscle structure seen in children with CP imply loss of muscle functional units or sarcomeres [14]. Muscle

structure parameters affecting number of sarcomeres in parallel such as muscle thickness have been significantly correlated to strength development in both children with CP and TD [8–10]. However, the scientific literature has shown conflicting results regarding muscle structure parameters reflecting number of sarcomeres in series such as fascicle length which determine muscle excursion and velocity [11]. This parameter has been considered of great importance for it determines muscle excursions and thus the range through which the muscle can develop muscle force and power, maximum shortening speed, and length at which passive force can be developed [15]. Muscle fascicle length has been assessed primarily at the ankle plantar-flexor muscles, of great functional importance to locomotion, and has shown either significantly reduced [16–19] or no significant differences [15,20–24] in fascicle length for children with CP as compared to TD children (Table 1). Furthermore, and contrary to what might be expected, correlations of fascicle length to muscle rate of force development have not been found for children with CP [9].

The lack of correlation between muscle fascicle length and rate of force development in children with CP could be due, on the one hand, to the non-optimal joint position adopted for force generation on the isometric strength tests as compared to the position of TD children, thus different fascicle lengths [25,26]. On the other hand, the lack of correlation could be due to the erroneous assumption that muscle fascicle length is representative of sarcomere number and length [7]. However, fascicle length regulation appears to be impaired in children with CP and thus shorter or equal fascicle lengths than TD children may imply greater sarcomere lengths and operate on the descending limb of the sarcomere length–tension curve [23] (see Fig. 1).

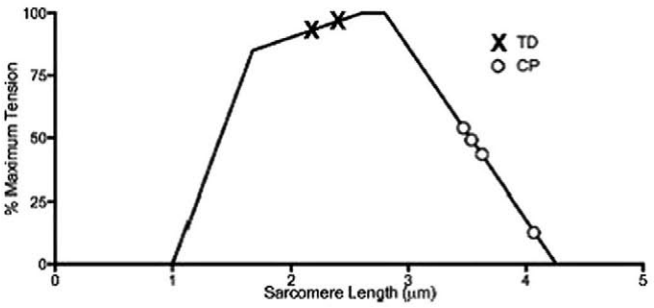

Fig. 1. Schematic length–tension curve of the skeletal muscle. Muscles of children with cerebral palsy (CP) and typically developing (TD) children are positioned on the curve to depict where their muscles operate [23].

Accordingly, dynamic strength assessments accounting for differences in optimal position for force development and sarcomere length measurements should be used to find correlations. Unfortunately, sarcomere length assessment is difficult and therefore relative muscle fascicle excursions have been proposed as an estimation of sarcomere excursion [16].

The hypothesis

We hypothesize that relative fascicle excursions in children with CP would be significantly correlated to dynamic muscle strength. Furthermore, these correlations would be similar to those of TD children. This would imply that children with CP presenting

Table 1
Review of plantar-flexor fascicle lengths in children with CP and TD children.

Refs.	Sample		Age (years)	Level	GMFCS	Muscle	Measure	Knee (deg)	Ankle (deg)	Normalized	Difference CP-TD (%)
[20]	CP	$n=7$	10.0 (6–13)	Di = 7	–	MG	D	0	−30	Yes	17.46
	TD	$n=5$	7.8 (7–11)						Rest	Yes	−9.00
									−30	No	6.00
									Rest	No	−15.00
[21]	CP	$n=16$	7.8 (4–12)	H = 16	–	MG	M	0	Rest	Yes	−4.46
	TD	$n=15$	9.5 (4–13)						MDF	Yes	3.00
									Rest	No	−16.00*
									MDF	No	−8.00
[22]	CP	$n=20$	8.5 (1.9)	–	–	MG	D	0	Rest	Yes	−16.67
	TD	$n=21$	8.8 (2.2)								
[15]	CP	$n=15$	3.7 (1.2)	H = 5 Di = 10	I = 10, II = 5	MG	M	0	Rest, MDF	Yes	0.00
	TD	$n=20$	4.0 (1.7)						MPF	Yes	+*
[24]	CP	$n=9$	17.0 (2.0)	–	I = 9	MG	–	0	MDF	–	−17.00
	TD	$n=10$	18.0 (2.0)								
[23]	CP	$n=20$	12.1 (5.3)	–	–	SOL	–	–	MDF	Yes	2.86
	TD	$n=21$	12.4 (3.4)						−30		
[16]	CP	$n=11$	13.3 (1.5)	Di = 6, H = 1, Q = 4	I = 2, II = 1, III = 4, IV = 4	MG	M	45	0	–	−43.00*
	TD	$n=14$	11.8 (2.6)								
[17]	CP	$n=12$	10.9 (2.6)	Di = 5, H = 7	II = 2, III = 1, IV = 2	MG	D	0	−20	Yes	–*
	TD	$n=11$	12.6 (2.3)						−10	Yes	–*
									0	Yes	–*
									10	Yes	–*
								90	−20	Yes	–*
									−10	Yes	–*
									0	Yes	–*
									10	Yes	–*
[18]	CP	$n=8$	10.2 (5.0)	H = 8, P = 8, NP = 8	II = 7, III = 1	MG	P, M, D		Rest	–	−16.67*
	TD	–	–								
[19]	CP	$n=18$	5.7 (3.9)	Di = 18	II = 12, III = 1	MG	P, M, D		Rest	Yes	−10.00*
	TD	$n=50$	9.1 (2.3)							No	−21.00*

*CP (cerebral palsy), TD (typically developing), H (hemiplegia), Di (diplegia), Q (quadriplegia), P (paretic leg), NP (non-paretic leg), MDF (maximum dorsi-flexion), MG (medial gastrocnemius), SOL (soleus), D (distal), M (medial), P (proximal), GMFCS (Gross Motor Functional Classification System). *Dorsiflexion (+), plantarflexion (−). *Age Mean(SD) or (range).

high relative fascicle excursions, would have decreased dynamic strength, which would in turn affect gait. Consequently, treatment prescription and assessment of treatment outcomes could be substantially improved.

With over-stretched sarcomere lengths and without stimulating addition of sarcomeres in series, we believe these subjects would look to increase force development through the passive tension component of the muscle as passive tissue force increases exponentially with increasing stretch [27,28]; or eccentric strength development which is maintained to a greater degree than concentric strength, with high eccentric/concentric ratios [29], in children with CP. This suggests that increased sarcomere lengths would possibly result in crouch gait as a compensatory strategy. Furthermore, relative muscle fascicle excursions could be used as a predictive variable of outcomes related to crouch gait prevention treatments such as strength training.

Evaluation of the hypothesis

To what point is muscle architecture responsible for muscle weakness in children with CP? Scientific literature regarding the impact of muscle architecture, including muscle fascicle length, on different expressions of force generating capacity in children with CP is scarce. Nevertheless, this has been studied for knee extensors and flexors [8–10] which highlight the different muscle architecture correlations to strength between children with CP and TD children.

Correlations between muscle architecture measurements and isometric maximal voluntary contractions (MVC) have been shown for rectus femoris and vastus lateralis muscle thickness, more so for TD children than for children with CP and more so for the vastus lateralis than for the rectus femoris [8]. In addition, children with CP exhibited a much lower muscle thickness correlation to MVC for the rectus femoris than for the vastus lateralis. This could be explained through the fact that while the rectus femoris is better suited for greater velocity and displacement due to its larger fiber length/physiological cross sectional area (PCSA) ratio, the vastus lateralis is more suited for force production due to its small fiber length/PCSA ratio and thus the greater correlation to MVC [30,31]. On the contrary, no correlations were observed between muscle fascicle length or pennation angle and MVC for either vastus lateralis or rectus femoris [8]. Because fascicle length is related to velocity of force production, we believe strength measures which take velocity into account may shed significant correlations to fascicle length.

Regarding strength measurements focused on velocity of force generation, vastus lateralis and rectus femoris muscle thickness, pennation angle, and fascicle length for TD children have been shown to be significant predictors of peak rate of force development (RFD) and impulse which depends on both strength and velocity of strength development [9]. However, for children with CP, only vastus lateralis muscle thickness was a significant predictor of peak RFD and impulse [9]. This later finding might seem odd, as muscle fascicle length would be expected to correlate with measurements of velocity of force generation. Especially for the rectus femoris muscle which is a velocity specialized muscle [30].

We believe that the joint position adopted which directly affects fascicle length might have not been optimal for force generation in children with CP [25,26]. Thus the lack of correlation between muscle fascicle length and velocity of force generation. Therefore, strength assessments that take into account muscle strength development throughout the full range of motion (ROM) should be considered [10]. In addition, sarcomere length, which closely relates to force production and velocity of force generation measurements, is often mistakenly reported as fascicle length [7]. Therefore, sarcomere length and number should be addressed instead of fascicle length. This should also account for the inconsistencies in muscle fascicle length differences between children with CP and TD children [11].

Regarding joint position adopted during isometric testing, it might not be optimal for force generation as subjects with CP have shown to generate different force at different joint positions [25,26]. Regarding isometric force production in children with CP, the greatest strength reduction between independent and dependent gait was at the hip abductor and knee extensor levels at non-optimal positions for force production compared to TD children [25]. Furthermore, this study compared peak isometric torque production at 90° and 30° of knee flexion and found a 62.7% reduction in peak torque for 30° of knee flexion with respect to 90° in children with CP. This finding is indicative of the effect of joint position on force production [25]. Similarly, abductor peak isokinetic strength in children with CP occurred earlier in the ROM than in TD children while the hip was still in adduction [26] indicating a joint position dependency of force production. In this sense, Reid et al. (2014) assessed muscle morphology and structure effects on muscle performance through isokinetic assessments taking joint position into account. This study found high correlations between muscle volume and isokinetic joint work development for children with CP and to the same extent as TD children. Isokinetic assessment of joint work would therefore not be influenced by neural drive, accounts for joint position differences for optimal performance, and better addresses functional capacity of children with CP. Unfortunately, correlations to fascicle length, a muscle architecture parameter affecting measures of velocity of force generation, and correlation to function was not measured.

As stated earlier, results regarding muscle fascicle length of children with CP have been inconsistent [11] showing both shorter [16–19,30] and equal [15,20–22] fascicle lengths when compared to TD children. Furthermore, differences in muscle fascicle length and strength correlations between TD children and children with CP have been observed [8,9]. While for TD children correlations were observed between muscle fascicle length and MVC, RFD, or impulse, this was not found in children with CP [8,9]. The lack of correlation and the inconsistent results may be explained by the erroneous assumption that muscle fascicle length is representative of sarcomere length which closely relates to force production and velocity of force generation [7,16]. For example, small fascicle lengths may have non-optimal, over-stretched, sarcomere lengths, which has been observed for children with CP [7,14,23,28,32–34] (Table 2). Moreover, correlations between sarcomere length and dynamic assessments of strength and power, which may reveal a significant correlation, have not been carried out to date. This would be of great clinical significance as power generation has been highly correlated to functional performance in children with CP both generally [35,36] and analytically [4,31]. Furthermore, isometric RFD and impulse have been significantly and positively associated to function [9]. Therefore, when searching for a correlation between sarcomere length and strength, we believe that dynamic submaximal joint power assessment taking into account joint position would be better suited.

Sarcomere length, has been defined as the best predictor of active muscle force, and has recently been shown to be longer in children with CP as compared to TD subjects [7] at the soleus [23], hamstrings [32], flexor carpi ulnaris [33,34], and extensor carpi radialis brevis [33]. On the contrary, shorter [38,39] or equal [32] sarcomere lengths have been observed. However, this was measured at muscle slack length or resting length, at which no force would be transmitted to the tendon. Furthermore, sarcomeres have been estimated to be short as active force has been reported to be significantly high and passive force small for FCU at maximum wrist extension angle. Nevertheless, joint ROM was limited and showed a great variability between subjects [40]. As

Table 2
Review of sarcomere lengths in children with CP and TD children.

Refs.	Control	CP	Muscle	Position	TD(μm)	SD	CP(μm)	SD	Difference CP-TD (%)	
[23]	$n = 21$ (11F, 12.4 y ± 3.4)	$n = 20$ (7F, 12.1 y ± 5.3)	SOL	Maximum DF	2.17	0.24	4.07	0.45	1.9	*
[28]	$n = 24$ (11.1 ± 5.1 y)	$n = 13$ (47.7 ± 15.13 y)	GAS	Stretched	2.6	–	3.71	0.44	1.11	*
			SOL		2.2	–	4.07	0.45	1.87	*
[32]	$n = 19$ (11F, 15.8 y ± 1.8)	$n = 33$ (10F, 9.6 y ± 4.2) GMFCS I (2), II (13), III (2), IV (6), V (10)	GRA	90 Hip and knee flexion	≈2.9	–	3.54	0.14	0.64	*
			SEMIT		≈3.1	–	3.62	0.13	0.52	*
[33]	Model	$n = 13$ (14.3 ± 2.9 y)	FCU	−30	3.1	–	4.2	0.3	1.1	*
				0	3.5	–	4.6	0.3	1.1	*
				30	3.8	–	5.1	0.2	1.3	*
			ECRB	−30	3.2	–	4.6	0.3	1.4	*
				0	3.1	–	3.9	0.2	0.8	*
				30	2.8	–	3.6	0.2	0.8	*
[34]	$n = 12$	$n = 6$ (3F, CP = 5, H = 1)	FCU	90 Flexion	2.41	0.31	3.48	0.44	1.07	*
				90 to 45 ± 15	Sarcomere length increased linearly with angle change					
[38]	$n = 29$ (14F, 19 y(5–40))	$n = 10$ (7F, 45 y(21–62))	FCU	Myofiber slack length	2.44	0.06	2.52	0.08	0.08	–
				Fascicle slack length	2.51	0.07	2.49	0.05	−0.02	–
[39]	$n = 38$ (37.4 ± 4.1 y)	$n = 15$ (7.8 ± 1.3 y)		Resting	2.2	0.04	1.84	0.05	−0.36	*

* CP (cerebral palsy), TD (typically developing), SOL (soleus), GAS (gastrocnemius), GRA (gracilis), SEMIT (semitendinosus), FCU (flexor carpi ulnaris), ECRB (extensor carpi radialis brevis), GMFCS (Gross Motor Functional Classification System), ≈ (estimated from graph), PF (plantarflexion), y (years), H (hemiplegia).

stated earlier, be believe that measurement of muscle sarcomere length at functional positions is better suited than muscle fascicle length measurement.

However, direct assessment of sarcomere length is difficult and thus other techniques should be considered. Recently, relative fascicle excursion measurement has been suggested as an indirect measure of sarcomere excursion and length [16] assuming that children with CP have reduced in-series sarcomere number [12,23,41]. Matthiasdottir et al., (2014) observed that offset by a reduced number of sarcomeres in series, relative sarcomere excursions of the spastic gastrocnemius were larger and covered the descending limb of the human sarcomere force–length relationship (over-stretched sarcomere length) therefore reducing ROM and increasing weakness [14,16]. A similar reasoning can be followed for muscles, which may not be spastic, but as opposing muscles to the spastic ones chronically rest at a lengthened position and may not shorten sufficiently to generate required force [3]. Unfortunately, relative fascicle excursions have only been studied for the gastrocnemius [16] and correlations of this parameter to function, as in power generation during gait, have never been studied. Nevertheless, some studies have assessed absolute fascicle length excursion through ROM and enabled calculations of relative fascicle excursions [17,42]. One study showed that relative fascicle excursions are greater for children with CP when compared to TD children in gastrocnemius medialis at 0° knee flexion and soleus [17] which has been stated previously [16]. This may indicate greater sarcomere excursions throughout the ankle ROM.

From the later reasoning, it may be derived that subjects with CP presenting muscle weakness due to over-stretched sarcomeres may develop impaired gait as they are operating on the descending limb of the length–tension curve and would not be able to generate sufficient force or power. With over-stretched sarcomere lengths and without stimulating addition of sarcomeres in series, we believe these subjects would look to increase force development through other mechanisms. Proposed mechanisms are the use of the passive tension component of the muscle as passive tissue force increases exponentially with increasing stretch [27] or sarcomere length for children with CP [28,32]; or the use of eccentric strength development which is maintained to a greater degree than concentric strength, with high eccentric/concentric ratios [29], in children with CP. This suggests that increased sarcomere lengths would possibly result in crouch gait as a compensatory strategy. Crouch gait, which increases external joint moments may eventually lead to the loss of gait when strength development cannot meet the high demands exerted on the joints [43].

Muscles may be able to comply with walking demands through their adaptation to different mechanical stimuli targeting both an increase of sarcomeres in series, thus a reduction of sarcomere over-stretch, and in parallel to therefore prevent crouch gait through overloading or overstretching [27]. Studies of resistance training for children with CP have focused on progressive resistance training and results are inconsistent [44,45]. Nevertheless, there are alternative strengthening strategies that have been scarcely used in children with CP which should be considered. Eccentric strength training [46] and high velocity concentric training [37] have resulted in positive muscle alterations leading to increased strength which may be related to longitudinal muscle adaptations.

Eccentric resistance training alone has been shown to increase muscle fiber length to a greater extent than concentric resistance training alone in TD children [47]. During eccentric strength training an increase in muscle fascicle length and a reduced pennation angle through ROM has been observed in TD children [47]. In children with CP, this stimulus, significantly increased eccentric torque, work, and mean curve width towards normative values, meaning greater force generation through a greater ROM [26,46]. Furthermore, TD children showed an increased fascicle length more so in eccentric training as compared to concentric training [46].

As addressed earlier, not only do children with CP have reduced strength development [8], they also have reduced power development [9]. Power training which combines both force and velocity components may be beneficial as it targets both strength development (through increase of sarcomeres in parallel) and velocity development (through increase of sarcomeres in series) which has been greatly associated to functional activities [9]. Moreau et al. (2012) observed that the combination of RFD and MVC predicted 77% of variance in overall gait function, which might be due to the fact that each variable accounts for different functions during gait, power and force respectively. Furthermore, muscles with different functions (power and force) should also be combined as together they better predict performance on functional scales than alone [8].

Muscle power would be adversely affected by decreases in muscle size and fascicle length, as well as other neural factors such as voluntary activation deficits. This is the case for children with CP [3]. Muscle adaptation is specific to the applied stimulus [27]. Therefore, if the target is muscle power improvement through muscle structure adaptation, training at high velocities would be necessary [37].

To our knowledge, there is only one study addressing power training, or high velocity training, in children with CP [37]. This study observed an increase in peak power and velocity generation, rectus femoris muscle length, and functional performance and gait. More specifically, both high velocity training and progressive resistance training elicited increases in peak torque while peak power and velocity were only increased with the high velocity training. Regarding muscle architecture, results showed that muscle adaptation was specific to the training type and the muscle. There was a higher increase in rectus femoris fascicle length and CSA with high velocity training, while traditional progressive resistance training only elicited vastus lateralis muscle thickness and rectus femoris CSA increase, and rectus femoris fascicle length decrease. Finally, regarding gait and functional performance, improved performance assessed through the self-selected and fast walking speed, time up and go test and the 1-min walk test, was only seen following high velocity training. Plyometric training should also be considered as it combines eccentric and concentric contractions at high velocity and has shown improvement in gross motor ability, agility, and power for the upper extremity in children with CP [36]. However, the effects of plyometric training on lower limb performance in children with CP has not been studied to date.

As reported, the scientific literature regarding muscle architecture longitudinal adaptations to strength training has focused on muscle fascicle length and not sarcomere length. Given the inconsistencies which have been reported previously regarding muscle fascicle length, we believe sarcomere length adaptations should be monitored instead.

We have previously stated that offset by a reduced in-series sarcomere number, children with CP present over-stretched sarcomeres and may adopt crouch gait to increase passive tension [30]. However, sarcomere number may be increased in order to reestablish the optimal sarcomere length, which has been observed in overstretched stimulated muscles [27]. Unfortunately, while fascicle length adaptations to resistance training have been studied for children with CP, sarcomere length adaptations have not been addressed.

Nevertheless, we have found that extracted relative fascicle excursions at 90° knee flexion, have shown to be reduced in the gastrocnemius medialis through functional strength training and stretching in children with CP [42]. This may indicate smaller sarcomere excursions throughout the ankle ROM in response to functional strength and flexibility training. To our knowledge, no study has addressed changes in relative fascicle excursions as a response to training which should be assessed in future studies.

In summary, when correlations of muscle fascicle length to velocity of force generation measurements were examined, no correlation was found for children with CP [9]. This lack of correlation might be due to non-optimal muscle fascicle length for the joint position adopted for force generation [25,26] or the erroneous assumption that muscle fascicle length is representative of sarcomere length and number. Therefore our research question would be: Are relative fascicle excursions of the ankle plantar-flexors correlated with plantar-flexor power development during the push-off phase of the gait cycle in children with CP as compared to TD children? We hypothesize that indirect measurements of sarcomere length in children with CP would be significantly correlated to power development during the push-off phase of the gait cycle. Furthermore, these correlations would be similar to those of TD children.

In addition, due to the reduced force development capacity, children with CP may look to increase force development through compensatory mechanisms. Proposed mechanisms are the use of the passive tension component of the muscle as passive tissue force increases exponentially with increasing stretch [27,28]; or the use of eccentric strength development which is maintained to a greater degree than concentric strength, with high eccentric/-concentric ratios [29], in children with CP. This suggests that increased sarcomere lengths would possibly result in crouch gait as a compensatory strategy. Therefore the next research questions would be: Could relative muscle fascicle excursion determine which children with CP are at greater risk of developing crouch gait? Finally, if this were true, could muscle relative fascicle excursions be used as a predictor variable of crouch gait treatment outcomes?

To test the initial hypothesis, we propose a prospective study in which dynamic power of the ankle plantar-flexors during the push-off phase of the gait cycle are recorded through kinetic assessments. Furthermore, this would be tested for correlation to relative muscle fascicle excursions at the gastrocnemius medialis and soleus [16] assessed through ultrasound imaging, in TD children and in children with CP.

Consequences of the hypothesis

Understanding of the underlying mechanisms of weakness in children with CP is key for individualized prescription and assessment of muscle-targeted interventions. Testing the relationship between sarcomere length estimates and dynamic strength development in TD children and in children with CP may reveal similar significant correlations. This would imply that ultrasound measurements of relative fascicle excursion in key muscles for gait may be used for the detection of children operating on the descending limb of the length–tension curve. In turn, these children might be at greater risk of developing crouch gait and may respond differently to interventions aiming to prevent crouch gait. Treatments which aim to optimize sarcomere length could provide a greater range of force development and thus decrease the risk of developing crouch gait.

Conflict of Interest

There was no conflict of interest.

Acknowledgments

This manuscript has been developed as part of a Grant support for Ph.D. studies from the Spanish Government. Ministerio de Economía y Competitividad, Secretaría de Estado de Investigación, Desarrollo e Innovación.

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