

Article

Effect of Lower Extremity Muscle Strength on Aerobic Capacity in Adults with Cerebral Palsy

Jungwan You and Seungwook Choi *

Health and Wellness College, Sungshin Women's University 2, 34 da-gil, Bomun-ro, Seongbuk-gu, Seoul 02844, Korea; rocggi@hanmail.net

* Correspondence: swchoi@sungshin.ac.kr

Abstract: The purpose of this study is to analyze the effect of lower extremity muscle strength of HIP joint and KNEE joint on the aerobic capacity to provide the basic data for developing an exercise program that can effectively improve the aerobic capacity of adults with cerebral palsy (CP) by identifying the part of the lower extremity muscle. A total of 18 ambulant adults with CP were recruited for this study. Seven ambulant adults with CP were excluded because they did not achieve the criteria of maximal exercise. The data from 11 subjects (11 men) with CP were used for the analysis. The mean ($\pm$ SD) age, height, weight, and BMI of the subjects were 37.00 ± 12.72 years, 170.45 ± 6.37 cm, 67.02 ± 8.62 kg, and 23.09 ± 2.78 kg/m², respectively. To measure the muscle strength of HIP joint and KNEE joint in lower extremities, the variables of the isokinetic muscle strength and the muscular endurance were performed using the isokinetic equipment (Biodex Co., Shirley, NY, USA). For the isokinetic muscle strength measurement of HIP joint, the 45°/s protocol indicating the muscle power and the 300°/s protocol indicating the muscle endurance were used. Additionally, the measurement of KNEE joint was performed once on the left and right side, using the protocol of 60°/s indicating the muscle power and 300°/s indicating the muscular endurance. Progressive exercise tests were conducted on the treadmill (Quinton model—4500) using previously developed protocols targeting CP. The initial protocol speeds were 5 km/h⁻¹ and 2 km/h⁻¹ for the subjects who have been classified as Gross Motor Function Classification System (GMFCS) level I and II, respectively. Using a portable cardiopulmonary indirect breath-by-breath calorimetry system (MetaMax 3B; Cortex Biophysik, Leipzig, Germany), pulmonary ventilation (VE), respiratory exchange ratio (RER), and oxygen uptake (VO₂) have been persistently measured. HR monitor (Polar Electro, Kempele, Finland polar Co. RS-800) was used to measure heart rate (HR). A correlation analysis was conducted to find out how the lower extremity muscle strength and aerobic capacity with cerebral palsy are related. Therefore, as a result, VO_{2peak} among aerobic capacity displayed a significant positive correlation in 45° and 300°/s peak torque/BW of HIP joint, and with 60° and 300°/s peak torque/BW of KNEE joint. It was the same with 60°/s Agon/Antag ratio of KNEE Joint ($p < 0.05$). VE_{peak} showed a significant positive correlation with 45° and 300°/s peak torque/BW of HIP joint, as well as correlation with 60° and 300°/s peak torque/BW and 60°/s Agon/Antag ratio of KNEE joint ($p < 0.05$). However, HR_{peak} showed a significant positive correlation only in 45°/s peak torque/BW of HIP joint ($p < 0.05$). The result of step-wise analysis was to find out which muscle strength significantly affects VO_{2peak} and HR_{peak} among aerobic abilities in the lower extremity muscles of those disabled with cerebral palsy. Among the muscle functions of lower extremity muscle strength, 300°/s peak torque/BW of KNEE Joint was found to have the greatest effect on VO_{2peak} ($p < 0.001$). As a result, 300°/s peak torque/BW of KNEE Joint was found to be the predictable factor that could explain the VO_{2peak} in the disabled people with cerebral palsy at 67% ($R^2 = 0.661$). In particular, among the muscle functions of lower extremity muscle strength at 45°/s peak, torque/BW of HIP Joint was found to have the greatest effect on HR_{peak} ($p < 0.001$). As a result, this factor was found to be the predictable factor that could explain the HR_{peak} in disabled people with cerebral palsy at 39% ($R^2 = 0.392$). In this study, the muscle strength of the lower extremity of CP was closely related to the aerobic capacity, and the muscle endurance of KNEE Joint and the muscle power of HIP Joint were found to be important factors to predict the aerobic capacity of CP.



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1. Background

Cerebral palsy (CP) is a neurodevelopmental disorder that begins in infancy (childhood) and continues throughout life [1]. It represents a ‘motor disorder’ in which abnormal lesions occur in the overall part of the body (global physical) [2], such as the nervous system, the muscular system, and the skeletal system due to the brain damage that occurs before brain development has been completed [3]. Additionally, when there is a brain damage like the case of CP, the kinematic problems occur due to the abnormal muscle tension, abnormal reflexes, and movement patterns [4]. In addition, it is common that the normal posture cannot be maintained because the joint motion range (Range of Motion) is reduced due to the contraction and relaxation of involuntary muscle as well as the decrease in muscle mass due to the abnormal muscle development [5].

Previous studies on the skeletal muscle structure of CP reported, through a comparison between children with cerebral palsy and general children, that the muscle strength of children with cerebral palsy is weak because the length and thickness of muscle fibers are shorter and thinner than those of general children [6–13]. In a study measuring the sarcomeres in the flexor muscle fibers of the carpal muscle, both in the adolescents with spastic cerebral palsy and normal young adults, the length of the sarcomeres in the group with spasticity was found to be abnormally longer than that of the control group without spasticity [14]. The same study has reported that the elasticity of fiber bundles and single fiber is lower in children with cerebral palsy than in general children, even in childhood, because the extracellular matrix is delicate, its quality is poor, and its strength is weak [15]. In other words, although it is difficult to explain anatomically, the abnormal development of the CP muscle is thought to be due to the secondary loss of muscle length because of the lesions in the central nervous system. The problem of such abnormal muscle deformation is not only the important cause of muscle loss and muscle stiffness, but also that of the decreased motor ability of whole body.

For CP, low muscle strength affects the gait pattern [16,17] and decreases motor function [18] compared to normal people, so it can be thought that it will adversely affect aerobic capacity. Basically, the aerobic capacity refers to the ability to deliver oxygen to muscles, generate energy during exercise, and utilize it as one of the exercise abilities [19]. Additionally, it is an important indicator for predicting the adult health, diseases [20,21], the cardiopulmonary function and the mortality rate [22]. Previous studies have reported that the aerobic capacity of CP is significantly lower than that of normal people [23–27]. A study comparing the aerobic capacity of 24 cerebral palsy children (16 males and 8 females) and general children reported that children with cerebral palsy had significantly lower aerobic capacity than that of general children, explaining that the involuntary muscle convulsion was the main reason [28]. In addition, a study comparing the aerobic capacity of adult CPs to that of general adults using arm ergometer reported that adult CPs had a significantly lower aerobic capacity because various muscle abnormalities and movement restrictions of adult CPs lead to the motor abnormality [25]. In conclusion, CP manifests the combination of problems related to the muscle weight loss, muscle cramp, stiffness, and rigidity due to the abnormal muscle fiber development. These abnormal movements and gait patterns cause such phenomenon, adversely affecting the aerobic capacity.

Among the muscle strengths of the whole body, that of the lower extremities is closely related to the aerobic capacity [29]. Although the following is not the result of a study targeting people with cerebral palsy, it was reported that when the selective training was performed only on the lower extremities without full body training in patients with chronic heart failure, as the muscle strength of the lower extremities increased, the breathing difficulties felt at the same intensity of exercise decreased, and at the same time, the muscle strength of the flexor muscle of the KNEE joint increased, as well as the maximum oxygen

intake [29]. In other words, it was suggested that both the increase in peak oxygen uptake (VO_{2peak}) and the increase in muscle strength in the lower extremities had a positive effect on reducing dyspnea [30]. Additionally, it was reported that there was a positive correlation between the instantaneous lower extremity muscle strength and the cardiopulmonary function [31]. It was reported that there was a positive correlation between the peak oxygen uptake and the muscle strength of the KNEE extensor, and the afferent contraction was more closely related to the peak oxygen uptake (VO_{2peak}) than the eccentric contraction in the study comparing the relationship between the peak oxygen uptake and the lower extremities muscle strength according to the speed and contraction pattern of muscle contraction in the KNEE extensor [32]. There was only one study on CP, and it concluded that VO_{2peak} increased significantly as a result of 8 weeks of upper and lower limb training using Schwinn Air-Dyne ergometer in 7 CPs [33]. In other words, the high muscle strength of the lower extremities is closely related to obtaining high aerobic capacity, which can be thought to have a more positive effect on the disabled with cerebral palsy as well as normal people.

Looking at the studies on the motor ability of CP so far, most of the studies were conducted on children, not adults [34–37]. However, contrary to the past claims that muscle tissue will not change continuously in the patients with the brain injury and brain lesion, recent studies have reported that the skeletal muscle in CPs consistently exhibits different denaturation patterns from those of normal muscle depending on the several factors and causes the clinically observed weakness [15]. In addition, they pointed out the problems and seriousness of the secondary motor dysfunction and changes that occur in adult cerebral palsy [38–45]. Additionally, there are many studies comparing the correlation between lower limb muscle strength and aerobic capacity in normal people or in other diseases, but no studies have yet examined the correlation of lower limb muscle strength and the aerobic capacity of adult CPs.

Therefore, in order to investigate the relationship between the lower extremity muscles strength of CP and the aerobic capacity, this study measured the lower extremity muscle strength (Extension and Flexion of the KNEE joint, Extension and Flexion of the HIP joint) and the aerobic capacity in adults with cerebral palsy, but not of children with cerebral palsy. Therefore, the purpose of this study was to analyze the effect of lower extremity muscle strength on the aerobic capacity and to provide the basic data for developing the exercise program that can effectively improve the aerobic capacity of adults with cerebral palsy by identifying the part of the lower extremity muscle that is most closely related to the aerobic capacity.

2. Methods

This study was approved by the ethical committee of the Center for Research Ethics, Sungshin Women's University. The investigation conforms to the Declaration of Helsinki. All subjects gave written, informed consent before participating in the study.

- (1) Participants: This study was conducted from April 2019 to June 2020 in the Seoul Municipal CP welfare center in Korea. A total of 18 ambulant adults with CP were recruited for this study. 7 ambulant adults with CP were excluded because they did not achieve the criteria of maximal exercise. Thus, the data from 11 subjects (11 men) with CP were used for the analysis. The mean ($\pm$ SD) age, height, weight, and BMI of the subjects were 37.00 ± 12.72 years, 170.45 ± 6.37 cm, 67.02 ± 8.62 kg, and 23.09 ± 2.78 kg/m², respectively.
- (2) Lower extremity muscle strength measurement (Isokinetic exercise test): To measure the muscle strength of HIP joint and KNEE joint in lower extremities, the variables of the isokinetic muscle strength and the muscular endurance were performed using the isokinetic equipment (Biodex Co, Shirley, NY, USA). The range of motion (ROM) of all joints was as follows: 0° of maximum extension was set as neutral, the range of flexion was set as 90° bent from the neutral position, and gravity compensation was performed in the state of flexion of about 15°. For accurate measurement during the

test, a dynamometer coincided in the motion axis of each test joint, and the subjects were given an accurate understanding of the test and practiced three times before the test. For the isokinetic muscle strength measurement of HIP joint, the $45^\circ/\text{s}$ protocol indicated the muscle power and the $300^\circ/\text{s}$ protocol indicating the muscle endurance were used. Additionally, the measurement of KNEE joint was performed once on the left and right side using the protocol of $60^\circ/\text{s}$, indicating the muscle power and $300^\circ/\text{s}$ indicating the muscular endurance. Then, the results of peak torque % body weight (%) and Agon/Antag ratio (%) of the agonist and antagonist muscle, both in the left and right side, were analyzed using the average value.

- (3) Aerobic capacity measurement: Progressive exercise tests were conducted on the treadmill (Quinton model- 4500) using previously developed protocols targeting CPs [28,46]. The initial protocol speeds were 5 km/h^{-1} and 2 km/h^{-1} for the subjects who has been classified as GMFCS level I and II, respectively. There was a speed increase at a rate of 0.25 km/h^{-1} every minute until it was terminated voluntarily. The subjects were verbally instructed to continue until they felt the exhaustion. Using a portable cardiopulmonary indirect breath-by-breath calorimetry system (MetaMax 3B; Cortex Biophysik, Leipzig, Germany), pulmonary ventilation (VE), respiratory exchange ratio (RER), and oxygen uptake (VO_2) were persistently measured. A HR monitor (Polar Electro, Kempele, Finland polar Co. RS-800) was used to measure heart rate (HR). During the gait on the treadmill, peak VE (VE_{peak}) and peak RER were defined as values measured when $\text{VO}_{2\text{peak}}$ was detected. The subjects had the mission to accomplish two of the following three criteria for the results to be accepted with $\text{VO}_{2\text{peak}}$: (1) RER value greater than 1.0, (2) The value of heart rate greater than the predicted heart rate ($[220 - \text{age}] \times 0.85$), or (3) a plateau (increase of $<150 \text{ mL} \cdot \text{min}$ of oxygen) in O_2 with increasing work rates. To avoid the effect on the metabolic response and HR of the subjects, they were told to avoid excessive physical activity for 24 h before testing and to refrain from any stimulating substances (alcohol, coffee, tobacco, and so on) or any drugs which could interfere with the experiment. Subjects had their last meal 3 h prior to the initiation of the test.

3. Results

These are the results of measuring the lower extremity muscle strength and the aerobic capacity of disabled people with cerebral palsy (Table 1). The lower extremity muscle strength measured peak torque/BW to be 105.49 ± 33.35 at $45^\circ/\text{s}$ of HIP Joint and Agon/Antag ratio was 226.15 ± 119.20 . Additionally, peak torque/BW was 120.23 ± 47.13 at $300^\circ/\text{s}$ and Agon/Antag ratio was 199.43 ± 91.60 . For the KNEE Joint at $60^\circ/\text{s}$, peak torque/BW was 167.43 ± 39.72 and Agon/Antag ratio was 45.87 ± 12.09 . In addition, the KNEE Joint at $300^\circ/\text{s}$, peak torque/BW was 106.90 ± 18.88 and Agon/Antag ratio was 77.09 ± 9.86 . Finally, the aerobic capacity was 37.63 ± 8.12 for $\text{VO}_{2\text{peak}}$ (mL/kg/min), 78.71 ± 23.00 for VE_{peak} (l/min), and 186.90 ± 12.05 for HR_{peak} (beats/min).

This is the result of correlation analysis to find out the relationship between the lower extremity muscle strength and the aerobic capacity of disabled people with cerebral palsy (Table 2). As such, $\text{VO}_{2\text{peak}}$, among aerobic capacities, displayed a significant positive correlation in 45° and $300^\circ/\text{s}$ peak torque/BW of HIP joint, and with 60° and $300^\circ/\text{s}$ peak torque/BW of KNEE Joint. In addition, it was the same with $60^\circ/\text{s}$ Agon/Antag ratio of KNEE Joint ($p < 0.05$). Likewise, VE_{peak} showed a significant positive correlation with 45° and $300^\circ/\text{s}$ peak torque/BW of HIP joint along with the same correlation with 60° and $300^\circ/\text{s}$ peak torque/BW and $60^\circ/\text{s}$ Agon/Antag ratio of KNEE Joint ($p < 0.05$). However, HR_{peak} showed a significant positive correlation only in $45^\circ/\text{s}$ peak torque/BW of HIP joint ($p < 0.05$).

Table 1. Comparison of the Lower Extremity Muscle Strength and Aerobic Capacity (mean $\pm$ SD).

(n = 11)		Lower Extremity Muscle Strength						
		HIP Joint				KNEE Joint		
		45°/s		300°/s		60°/s		300°/s
		peak torque/BW	Agon/Antag ratio	peak torque/BW	Agon/Antag ratio	peak torque/BW	Agon/Antag ratio	peak torque/BW
Mean $\pm$ S.D		105.49 $\pm$ 33.35	226.15 $\pm$ 119.20	120.23 $\pm$ 47.13	199.43 $\pm$ 91.60	167.43 $\pm$ 39.72	45.87 $\pm$ 12.09	106.90 $\pm$ 18.88
		Aerobic Capacity						
		VO _{2peak} (mL/kg/min)			VE _{peak} (l/min)		HR _{peak} (beats/min)	
Mean $\pm$ S.D		37.63 $\pm$ 8.12			78.71 $\pm$ 23.00		186.90 $\pm$ 12.05	

Table 2. Correlation Coefficients between Lower Extremity Muscle Strength and Aerobic Capacity.

	A1	A2	A3	A4	B1	B2	B3	B4	C	D
A2	0.594	-								
A3	0.892 **	−0.385	-							
A4	−0.515	0.690 *	−0.445	-						
B1	0.570	−0.098	0.533	0.148	-					
B2	0.435	−0.213	0.581	−0.091	0.609 *	-				
B3	0.600	−0.172	0.656 *	−0.135	0.874 **	0.635 *	-			
B4	0.105	−0.092	0.258	−0.184	0.339	0.514	0.505	-		
C	0.745 **	−0.351	0.767 **	−0.490	0.658 *	0.610 *	0.813 **	0.361	-	
D	0.667 *	−0.392	0.638 *	−0.215	0.736 **	0.635 *	0.869 **	0.260	0.745 **	-
E	0.626 *	−0.432	0.499	−0.435	0.349	0.394	0.474	−0.173	0.729 *	0.739 *

* $p < 0.05$, ** $p < 0.01$. Note. A: HIP (A1: 45°/s peak torque/BW, A2: 45°/s Agon/Antag ratio, A3: 300°/s peak torque/BW, A4: 300°/s Agon/Antag ratio), B: Knee (B1: 60°/s peak torque/BW, B2: 60°/s Agon/Antag ratio, B3: 300°/s peak torque/BW, B4: 300°/s Agon/Antag ratio), C: VO_{2peak}, D: VE_{peak}, E: HR_{peak}.

This is the result of step-wise analysis to find out which muscle strength significantly affects VO_{2peak} among aerobic abilities in the lower extremity muscles of those disabled with cerebral palsy (Table 3). Among the muscle functions of lower extremity muscle strength, 300°/s peak torque/BW of KNEE was found to have the greatest effect on VO_{2peak} ($p < 0.001$). As a result, 300°/s peak torque/BW of KNEE was found to be the predictable factor that could explain the VO_{2peak} in disabled people with cerebral palsy at 66% ($R^2 = 0.661$).

Table 3. Stepwise regression analysis for prediction of VO_{2peak}.

	B	Beta	p	R ² Change	R ²	F
KNEE 300°/s peak torque/BW	0.350	0.813	0.002	0.623	0.661	17.517 **

** $p < 0.01$.

This is the result of step-wise analysis to find out which muscle strength significantly affects HR_{peak} among aerobic abilities in the lower extremity muscles of those disabled with cerebral palsy (Table 4). Among the muscle functions of lower extremity muscle strength, 45°/s peak torque/BW of HIP, in particular, was found to have the greatest effect on HR_{peak} ($p < 0.001$). As a result, this factor was found to be the predictable factor that could explain the HR_{peak} in the disabled people with cerebral palsy at 39% ($R^2 = 0.392$).

Table 4. Stepwise regression analysis for prediction of HR_{peak}.

	B	Beta	p	R ² Change	R ²	F
HIP 45°/s peak torque/BW	0.226	0.626	0.039	0.325	0.392	5.812 *

* $p < 0.05$.

4. Discussion

So far, there have been more studies that investigated the motor abilities of children with cerebral palsy than those of adults with cerebral palsy [34–37]. Additionally, most of the studies examining the relationship between muscle strength and aerobic capacity were conducted on the general public or the diseased patients, not on those disabled with cerebral palsy [47–49]. Therefore, this study investigated the relationship between the muscle strength and the aerobic capacity in adults with cerebral palsy based on the fact that there is a close relationship between the muscle strength and the aerobic capacity.

As a result of correlation analysis, VO_{2peak} showed a significant positive correlation between 45° and $300^\circ/s$ peak torque/BW of HIP joint, 60° and $300^\circ/s$ peak torque/BW of KNEE, and $60^\circ/s$ Agon/Antag ratio of KNEE ($p < 0.05$). Additionally, $45^\circ/s$ peak torque/BW of HIP joint showed a significant positive correlation with HR_{peak} ($p < 0.05$). The characteristics of gait that generally appear in CPs are caused by the limited range of motion of HIP Joint and KNEE Joint, the excessive adduction and internal rotation of HIP, the tilt of front pelvis, the pelvic obliquity, and the persistent plantar flexion at the ankle [34,50]. Due to these factors, CP gait has the general characteristics of reduced heel strike, reduced gait speed, and reduced stride length, and these gait parameters (stride, gait speed, gait posture, heel strike, etc.) are closely related to the muscle strength, in which gait speed has an especially high correlation with the muscle strength [18]. In general, the muscle weakness and the decrease in gait ability in CP lower the efficiency of gait and require a lot of energy from the body, which affects the decrease in stride length [51]. In addition, it was reported that the high oxygen cost (poor gait economy) of CP comes from muscle co-activation and total body mechanical power [52,53]. Among all the factors that measured the lower extremity muscle strength in this study, the following factors showed a significant correlation with VO_{2peak} : $45^\circ/s$ peak torque/BW representing the muscle power of HIP, $300^\circ/s$ peak torque/BW representing the muscle endurance of HIP, $60^\circ/s$ peak torque/BW indicating the muscle power, and $300^\circ/s$ peak torque/BW indicating the muscle endurance of KNEE ($p < 0.05$). Additionally, $45^\circ/s$ peak torque/BW of HIP showed a significant correlation with HR_{peak} ($p < 0.05$).

This is consistent with the previous studies above which showed that the muscle strength of CP is closely related to gait ability and exercise ability, and it can be considered an important result that can explain the relationship between the lower limb muscle strength of CP and the gait ability and the exercise ability in CP. Eventually, the abnormal muscle development of CP degrades the lower limb muscle strength, which leads to the abnormal gait patterns. Therefore, it can be considered that it adversely affects the aerobic capacity as a result of inefficiently using a large amount of physical energy for gait, resulting in the decrease in aerobic capacity.

Additionally, in this study, $60^\circ/s$ Agon/Antag ratio of KNEE showed a significant positive correlation with VO_{2peak} ($p < 0.05$). In a previous study, the EMG pattern was used to observe the muscle movement during CP gait, and as a result, it was reported that the agonist and antagonist muscles around the joint contracted simultaneously [52]. In addition, it was reported to increase in the KNEE extensor and reduce the flexor by introducing CPs into the lower limb muscle strength enhancement program, which eventually resulted in the improved gait ability by increasing the stride, which was due to the improved abnormal balance of KNEE agonist and antagonist muscles [54]. It can be thought that the abnormal ratio of agonistic and antagonistic muscles of the KNEE to CP is a factor that can adversely affect not only gait ability but also exercise ability and is closely related to low aerobic capacity.

Previous studies have reported that the muscles of CP children are smaller [18,55] and weaker [53,56] than normal healthy children. Additionally, the muscle strength is correlated with the gait patterns [55,57] and the motor functions [58], and the muscle strength is more associated with the muscle function than the muscle convulsion [57]. In particular, Eek et al. (2008) reported in CP's Gross Motor Function Classification System (GMFCS) that the areas of the greatest muscle strength between Level I, in which CP can gait free of an

aid apparatus, and GMFCS Level III groups, where CP gaits with aid apparatus, are HIP Extension/Abduction and KNEE Extension muscles [11]. Additionally, in this study, $300^\circ/\text{s}$ peak torque/BW of KNEE was found to have the greatest effect on $\text{VO}_{2\text{peak}}$ of CP among lower extremities muscle strength ($p < 0.01$), and it was found to be the predictive factor that could explain $\text{VO}_{2\text{peak}}$ at the level of 66% in CPs. In addition, $45^\circ/\text{s}$ peak torque/BW of HIP was found to have the greatest effect on HR_{peak} ($p < 0.05$), and this factor was found to be the predictive factor that could explain the HR_{peak} of people with cerebral palsy at the level of 39%. Lack of flexibility and movement control of CP has been recognized as the main cause of the excessive energy use in the inefficient gait of CP. Previous studies investigated the energy requirement for CP adolescent gait, and as a result, 1.5 to 3 times of gait energy of normal adolescents was required depending on the degree and type of gait angle [59]. Additionally, the cost of gait was 3 times than that of normal adolescents [53]. To reduce the inefficient energy consumption during gait, CP adolescents require less convulsions, restoration of stability in posture changes, and removal of foot drag, all of which could be improved by strengthening the muscles of the torso and lower extremities, stressing the need for strengthening the muscle strength of lower extremities [58]. Additionally, the energy consumed during gait in CP children was investigated, and as a result, there was a close relationship between the KNEE extensor and the gait efficiency, suggesting that the KNEE extensor force is an important factor for the efficient use of energy [51]. On the other hand, although it was not a study related to CP, the two preceding studies investigated the kinetics of VO_2 by applying a heavy weight training program for normal adults. As a result, it was reported that the running economy improved as the storage of elastic energy increased, and the running economy improved due to the effect of titin on the elastic properties of muscle fibers [59,60]. As such, it can be thought that the lower limb muscle strength has a close relationship with the gait ability and also affects the aerobic capacity.

As a result, it can be concluded that the unstable gait pattern of the lower extremities of CP requires a lot of energy among the aerobic capacity measurements in this study, which resulted in the decrease in aerobic capacity. In particular, for CP, the muscle endurance of lower limb of KNEE Joint and the muscle power of HIP Joint are very important factors that can both enable the efficient gait and predict the aerobic capacity.

5. Conclusions

In this study, the muscle strength of the lower extremity of CP was closely related to the aerobic capacity, and in particular, the muscle endurance of KNEE Joint and the muscle power of HIP Joint were found to be important factors to predict the aerobic capacity of CP. In future studies, it is necessary to investigate how the intervention of muscle exercise programs focused on KNEE Joint and HIP Joint of CP affects the aerobic capacity enhancement. Based on the results of this study, it is considered that a follow-up study is needed to intervene in the exercise program to understand the causal relationship between muscle strength increase and aerobic capacity.

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Informed Consent Statement: All subjects gave written, informed consent before participating in.

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Abbreviations

CP: cerebral palsy; VO₂: oxygen uptake; HR: heart rate; VE: pulmonary ventilation; BW: body weight; Agon/Antag: agonist to antagonist; SD: standard deviation; GMFCS: gross motor function classification system.

References

- Rosenbaum, P.; Paneth, N.; Leviton, A.; Goldstein, M.; Bax, M.; Damiano, D.; Jacobsson, B. A report: The definition and classification of cerebral palsy. *NeoReviews* **2006**, *7*, e569. [\[CrossRef\]](#)
- Mutch, L.; Alberman, E.; Hagberg, B.; Kodama, K.; Perat, M. Cerebral Palsy Epidemiology: Where are We Now, and Where are We Going? *Dev. Med. Child. Neurol.* **1992**, *34*, 547–555. [\[CrossRef\]](#) [\[PubMed\]](#)
- Krigger, K.W. Cerebral palsy: An overview. *American family physician*. *Am. Fam. Physician* **2006**, *73*, 91–100.
- Knox, V.; Evans, A.L. Evaluation of the functional effects of a course of Bobath therapy in children with cerebral palsy: A preliminary study. *Dev. Med. Child. Neurol.* **2002**, *44*, 447–460. [\[CrossRef\]](#) [\[PubMed\]](#)
- Boyd, R.; Graham, H. Objective measures of clinical findings in the use of botulinum toxin type A for the management of children with cerebral palsy. *Eur. J. Neurol.* **1999**, *6* (Suppl. 4), 523–535.
- Shortland, A.P.; Harris, C.A.; Robinson, R.O. Architecture of the medial gastrocnemius in children with spastic diplegia. *Dev. Med. Child. Neurol.* **2002**, *44*, 158–163. [\[CrossRef\]](#)
- Elder, G.C.; Kirk, J.; Stewart, G.; Cook, K.; Weir, D.; Marshall, A.; Leahey, L. Contributing factors to muscle weakness in children with cerebral palsy. *Dev. Med. Child. Neurol.* **2003**, *45*, 542–550. [\[CrossRef\]](#)
- Lampe, R.; Grassl, S.; Mitternacht, J.; Gerdesmeyer, L.; Grading, R. MRT-measurements of muscle volumes of the lower extremities of youths with spastic hemiplegia caused by cerebral palsy. *Brain Dev.* **2006**, *28*, 500–506. [\[CrossRef\]](#)
- Malaiya, R.; McNee, A.E.; Fry, N.R.; Eve, L.C.; Gough, M.; Shortland, A.P. The morphology of the medial gastrocnemius in typically developing children and children with spastic hemiplegic cerebral palsy. *J. Electromyogr. Kinesiol.* **2007**, *17*, 657–663. [\[CrossRef\]](#)
- Mohagheghi, A.A.; Khan, T.; Meadows, T.H.; Giannikas, K.; Baltzopoulos, V.; Maganaris, C.N. In vivo gastrocnemius muscle fascicle length in children with and without diplegic cerebral palsy. *Dev. Med. Child. Neurol.* **2008**, *50*, 44–55. [\[CrossRef\]](#)
- Eek, M.N.; Tranberg, R.; Zügner, R.; Alkema, K.; Beckung, E. Muscle strength training to improve gait function in children with cerebral palsy. *Dev. Med. Child. Neurol.* **2008**, *50*, 759–764. [\[CrossRef\]](#) [\[PubMed\]](#)
- Moreau, N.G.; Teefey, S.A.; Damiano, D.L. In vivo muscle architecture and size of the rectus femoris and vastus lateralis in children and adolescents with cerebral palsy. *Dev. Med. Child. Neurol.* **2009**, *51*, 800–806. [\[CrossRef\]](#) [\[PubMed\]](#)
- Oberhofer, K.; Stott, N.S.; Mithraratne, K.; Anderson, I.A. Subject-specific modelling of lower limb muscles in children with cerebral palsy. *Clin. Biomech.* **2010**, *25*, 88–94. [\[CrossRef\]](#) [\[PubMed\]](#)
- Lieber, R.L.; Fridén, J. Spasticity causes a fundamental rearrangement of muscle-joint interaction. *Muscle Nerve* **2002**, *25*, 265–270. [\[CrossRef\]](#)
- Lieber, R.L.; Steinman, S.; Barash, I.A.; Chambers, H. Structural and functional changes in spastic skeletal muscle. *Muscle Nerve* **2004**, *29*, 615–627. [\[CrossRef\]](#)
- Desloovere, K.; Molenaers, G.; Feys, H.; Huenaerts, C.; Callewaert, B.; Van de Walle, P. Do dynamic and static clinical measurements correlate with gait analysis parameters in children with cerebral palsy? *Gait Posture* **2006**, *24*, 302–313. [\[CrossRef\]](#)
- Ross, S.A.; Engsberg, J.R. Relationships between spasticity, strength, gait, and the GMFM-66 in persons with spastic diplegia cerebral palsy. *Arch. Phys. Med. Rehabil.* **2007**, *88*, 1114–1120. [\[CrossRef\]](#)
- Damiano, D.L.; Abel, M.F. Functional outcomes of strength training in spastic cerebral palsy. *Arch. Phys. Med. Rehabil.* **1998**, *79*, 119–125. [\[CrossRef\]](#)
- Armstrong, N.; Welsman, J.R. Aerobic fitness: What are we measuring? *Med. Sport Sci.* **2007**, *50*, 5–25.
- Myers, J.; Prakash, M.; Froelicher, V.F.; Do, D.; Partington, S.; Atwood, J.E. Exercise capacity and mortality among men referred for exercise testing. *N. Engl. J. Med.* **2002**, *346*, 793–801. [\[CrossRef\]](#)
- Paffenberger, R.S.; Blair, S.N.; Lee, I.M. A history of physical activity, cardiovascular health and longevity: The scientific contributions of Jeremy N Morris, DSc, DPH, FRCP. *Int. J. Epidemiol.* **2001**, *30*, 1184–1192. [\[CrossRef\]](#) [\[PubMed\]](#)
- Brill, P.A.; Macera, C.A.; Davis, D.R.; Blair, S.N.; Gordon, N.E.I.L. Muscular strength and physical function. *Med. Sci. Sports Exerc.* **2000**, *32*, 412–416. [\[CrossRef\]](#) [\[PubMed\]](#)
- Balemans, A.C.; Van, W.L.; De Heer, S.J.; Van den Brink, J.; De Koning, J.J.; Becher, J.G.; Dallmeijer, A.J. Maximal aerobic and anaerobic exercise responses in children with cerebral palsy. *Med. Sci. Sports Exerc.* **2013**, *45*, 561–568. [\[CrossRef\]](#)
- Hoofwijk, M.; Unnithan, V.B.; Bar-Or, O. Maximal treadmill performance of children with cerebral palsy. *Ped. Exerc. Sci.* **1995**, *7*, 305–313. [\[CrossRef\]](#)
- Kusano, S.; Iwasaki, Y.; Tobimatsu, Y.; Suyama, T. Cardiorespiratory endurance and work efficiency of people with cerebral palsy measured using an arm ergometer. *J. Phys. Ther. Sci.* **2001**, *13*, 49–52. [\[CrossRef\]](#)

26. Tobimatsu, Y.; Nakamura, R.; Kusano, S.; Iwasaki, Y. Cardiorespiratory endurance in people with cerebral palsy measured using an arm ergometer. *Arch. Phys. Med. Rehabil.* **1998**, *79*, 991–993. [\[CrossRef\]](#)
27. Maltais, D.; Pierrynowski, M.; Galea, V.; Bar-Or, O. Physical activity level is associated with the O₂ cost of walking in cerebral palsy. *Med. Sci. Sports Exerc.* **2005**, *37*, 347–353. [\[CrossRef\]](#)
28. Verschuren, O.; Takken, T. Aerobic capacity in children and adolescents with cerebral palsy. *Res. Dev. Disabil.* **2010**, *31*, 1352–1357. [\[CrossRef\]](#)
29. Bergh, U.; Thorstensson, A.; Sjödin, B.; Hulten, B.; Piehl, K.; Karlsson, J. Maximal oxygen uptake and muscle fiber types in trained and untrained humans. *Med. Sci. Sports* **1977**, *10*, 151–154.
30. Beniaminovitz, A.; Lang, C.C.; LaManca, J.; Mancini, D.M. Selective low-level leg muscle training alleviates dyspnea in patients with heart failure. *J. Am. Coll. Cardiol.* **2002**, *40*, 1602–1608. [\[CrossRef\]](#)
31. Neder, J.A.; Nery, L.E.; Silva, A.C.; Andreoni, S.; Whipp, B.J. Maximal aerobic power and leg muscle mass and strength related to age in non-athletic males and females. *Eur. J. Appl. Physiol. Occup. Physiol.* **1999**, *79*, 522–530. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Kim, J.H.; Chung, S.G.; Han, T.R.; Oh, B.M.; Lee, G.J.; Lee, S.U. Relationship between Leg Strength of Concentric/Eccentric Mode and Maximal Oxygen Uptake. *Korean Soc. Sports Med.* **2005**, *23*, 137–143.
33. Pitetti, K.H.; Fernandez, J.E.; Lanciault, M.C. Feasibility of an exercise program for adults with cerebral palsy: A pilot study. *Adapt. Phys. Act. Q.* **1991**, *8*, 333–341. [\[CrossRef\]](#)
34. Johnson, D.C.; Damiano, D.L.; Abel, M.F. The evolution of gait in childhood and adolescent cerebral palsy. *J. Pediatric Orthop.* **1997**, *17*, 392–396. [\[CrossRef\]](#)
35. Rosenbaum, P.L.; Walter, S.D.; Hanna, S.E.; Palisano, R.J.; Russell, D.J.; Raina, P.; Wood, E.; Bartlett, D.J.; Barbara, E.; Galuppi, B.A. Prognosis for gross motor function in cerebral palsy: Creation of motor development curves. *JAMA* **2002**, *288*, 1357–1363. [\[CrossRef\]](#)
36. Bell, K.J.; Öunpuu, S.; DeLuca, P.A.; Romness, M.J. Natural progression of gait in children with cerebral palsy. *J. Pediatric Orthop.* **2002**, *22*, 677–682. [\[CrossRef\]](#)
37. Jahnsen, R. Being Adult with a ‘Childhood Disease’—A Survey on Adults with Cerebral Palsy in Norway. Doctoral Dissertation, University of Oslo, Oslo, Norway, 2004.
38. Andersson, C.; Mattsson, E. Adults with cerebral palsy: A survey describing problems, needs, and resources, with special emphasis on locomotion. *Dev. Med. Child. Neurol.* **2001**, *43*, 76–82. [\[CrossRef\]](#)
39. Bottos, M.; Feliciangeli, A.; Sciuto, L.; Gericke, C.; Vianello, A. Functional status of adults with cerebral palsy and implications for treatment of children. *Dev. Med. Child. Neurol.* **2001**, *43*, 516–528. [\[CrossRef\]](#)
40. Sandstrom, K.; Alinder, J.; Oberg, B. Descriptions of functioning and health and relation to gross motor function classification in adults with cerebral palsy. *Disabil. Rehabil.* **2004**, *26*, 1023–1031. [\[CrossRef\]](#)
41. Ando, N.; Ueda, S. Functional deterioration in adults with cerebral palsy. *Clin. Rehabil.* **2000**, *14*, 300–306. [\[CrossRef\]](#)
42. Gajdosik, C.G.; Cicirello, N. Secondary conditions of the musculo skeletal system in adolescents and adults with cerebral palsy. *Phys. Occup. Pediatr.* **2001**, *21*, 49–68. [\[CrossRef\]](#)
43. Jahnsen, R.; Villien, L.; Stanghelle, J.K.; Holm, I. Fatigue in adults with cerebral palsy in Norway compared with the general population. *Dev. Med. Child. Neurol.* **2003**, *45*, 296–303. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Jahnsen, R.; Villien, L.; Aamodt, G.; Stanghelle, J.K.; Holm, I. Musculoskeletal pain in adults with cerebral palsy compared to the general population. *J. Rehabil. Med.* **2004**, *36*, 78–84. [\[CrossRef\]](#) [\[PubMed\]](#)
45. Jahnsen, R.; Villien, L.; Egeland, T.; Stanghelle, J.K.; Holm, I. Locomotion skills in persons with cerebral palsy. *Clin. Rehabil.* **2004**, *18*, 309–316. [\[CrossRef\]](#) [\[PubMed\]](#)
46. Verschuren, O.; Takken, T.; Ketelaar, M.; Gorter, J.W.; Helders, P.J.M. Reliability and validity of data for 2 newly developed shuttle run tests in children with cerebral palsy. *Phys. Ther.* **2006**, *86*, 1107–1117. [\[CrossRef\]](#)
47. Ekdahl, C.; Broman, G. Muscle strength, endurance, and aerobic capacity in rheumatoid arthritis: A comparative study with healthy subjects. *Ann. Rheum. Dis.* **1992**, *51*, 35–40. [\[CrossRef\]](#)
48. Severinsen, K.; Jakobsen, J.K.; Overgaard, K.; Andersen, H. Normalized muscle strength, aerobic capacity, and walking performance in chronic stroke: A population-based study on the potential for endurance and resistance training. *Arch. Phys. Med. Rehabil.* **2011**, *92*, 1663–1668. [\[CrossRef\]](#)
49. Neil-Sztramko, S.E.; Kirkham, A.A.; Hung, S.H.; Niksirat, N.; Nishikawa, K.; Campbell, K.L. Aerobic capacity and upper limb strength are reduced in women diagnosed with breast cancer: A systematic review. *J. Physiother.* **2014**, *60*, 189–200. [\[CrossRef\]](#)
50. Rose, S.A.; Öunpuu, S.; DeLuca, P.A. Strategies for the assessment of pediatric gait in the clinical setting. *Phys Ther.* **1991**, *71*, 961–980. [\[CrossRef\]](#)
51. Kramer, J.F.; MacPhail, H.E.A. Relationships among measures of walking efficiency, gross motor ability, and isokinetic strength in adolescents with cerebral palsy. *Pediatr. Phys. Ther.* **1994**, *6*, 3–8. [\[CrossRef\]](#)
52. Unnithan, V.B.; Dowling, J.J.; Frost, G.; Bar-Or, O. Role of contraction in the O₂ cost of walking in children with cerebral palsy. *Med. Sci. Sports Exerc.* **1996**, *28*, 1498–1504. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Unnithan, V.B.; Dowling, J.J.; Frost, G.; Bar-Or, O. Role of mechanical power estimates in the O₂ cost of walking in children with cerebral palsy. *Med. Sci. Sports Exerc.* **1999**, *31*, 1703–1708. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Damiano, D.L.; Kelly, L.E.; Vaughn, C.L. Effects of quadriceps femoris muscle strengthening on crouch gait in adolescents with spastic diplegia. *Phys Ther.* **1995**, *75*, 658–671. [\[CrossRef\]](#) [\[PubMed\]](#)

-
55. Berger, W.; Quintern, J.; Dietz, V. Pathophysiology of gait in adolescents with cerebral palsy. *Electroencephalogr. Clin. Neurophysiol.* **1982**, *53*, 538–548. [[CrossRef](#)]
 56. Olney, S.J.; MacPhail, H.E.A.; Hedden, D.M.; Boyce, W.F. Work and power in hemiplegic cerebral palsy gait. *Phys. Ther.* **1990**, *70*, 431–437. [[CrossRef](#)]
 57. Horvat, M. Effects of a progressive resistance training program on an individual with spastic cerebral palsy. *Am. Corr. Ther. J.* **1987**, *41*, 7–11.
 58. Gage, J.R. Gait analysis: An essential tool in the treatment of cerebral palsy. *Clin. Orthop.* **1993**, *288*, 126–134. [[CrossRef](#)]
 59. Millet, G.P.; Jaouen, B.; Borrani, F.; Candau, R. Effects of concurrent endurance and strength training on running economy and VO₂ kinetics. *Med. Sci. Sports Exerc.* **2002**, *34*, 1351–1359. [[CrossRef](#)]
 60. Kyrolainen, H.; Kivela, R.; Koskinen, S.; McBride, J.; Andersen, J.L.; Takala, T.; Sipila, S.; Komi, P.V. Interrelationships between muscle structure, muscle strength, and running economy. *Med. Sci. Sports Exerc.* **2003**, *35*, 45–49. [[CrossRef](#)]