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Evaluation of the Cardiorespiratory Fitness in Fontan Patients By A Standardized Stair Climbing Test in Comparison to The Six Minute Walking Test and Cardiopulmonary Exercise Testing (CPET)

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Abstract

Introduction: Exercise testing is a valuable tool for assessing cardiorespiratory fitness (CRF), screening for early cardiovascular impairment in patients with congenital heart disease and evaluating medical treatments. This study aimed to assess the cardiorespiratory fitness of young univentricular patients following Fontan palliation using a simple stair climbing test (SCT). Additionally, the SCT was compared with established exercise tests, including the 6-minute walking test (6MWT) and standardized cardiopulmonary exercise testing (CPET) on a treadmill, the latter considered the "Gold standard". Methods: A cohort of 27 young Fontan patients, aged 7-29 years was included. Each patient underwent assessment of CRF through 6MWT and treadmill CPET according to the protocol recommended by the German Society of Pediatric Cardiology and Congenital Heart Disease (DGPK). Baseline vital signs (heart rate, oxygen saturation and blood pressure) were recorded before and immediately after each test. Parameters such as the walked distance, peak oxygen consumption VO2max [mL/min/kg] and [mL/min], maximum oxygen pulse and peak heart rate were documented. A standardized SCT protocol was developed, including stair climbing across four floors (13.14 m total vertical height) to elicit maximal exertion. Time to completion and vital parameters were recorded. Subjective exertion was evaluated using both the Borg - and Borg CR scale. To assess comparability among the CPET, 6MWT, and SCT, an SCT index was calculated to estimate the power output required to complete the stair climb. Results: Correlations among the SCT, 6MWT and CPET were evaluated. Our results showed a strong correlation between the walked distance during the 6MWT and the time achieved during the SCT (SCTt) ($r=-0.608$; $p=0.001$). Similar results were demonstrated by comparing the SCT index with the distance walked during the 6MWT ($r=0.423$; $p=0.031$). Furthermore, we could identify a significant correlation between SCTt and VO2max [mL/min/kg] during the CPET ($r=-0.650$; $p<0.0001$). Furthermore, a strong correlation was seen between the maximal heart rate achieved in SCT and CPET ($r=0.773$; $p<0.0001$). Even stronger correlation was observed between the VO2max (mL/min) during CPET and the SCT index ($r=0.808$; $p<0.0001$) as well as the SCT index and the peak oxygen pulse achieved during CPET ($r=0.723$; $p<0.0001$). Conclusion: The SCT could be used as a simple, cost- and time-efficient method to assess cardiorespiratory fitness in young univentricular patients after Fontan palliation. In addition, the stair climbing test could be integrated into routine follow-up protocols for this patient population. When applied regularly, the SCT may facilitate early detection of subtle declines in exercise capacity, thereby supporting proactive clinical management.

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Keywords: Fontan; spiroergometry; stair climbing test; cardiorespiratory fitness; cardiorespiratory exercise testing

Introduction

Between 3.1 and 4.9 infants of 10.000 live births are born with a single ventricle (SV) physiology [1, 2, 3, 4, 5].

The outcomes of patients treated with a Fontan procedure have improved significantly in recent decades due to improvements in diagnosis and surgical strategy [6, 7, 8, 9, 10]. Patients with a Fontan circulation today can achieve a higher quality of life and have a longer life expectancy than in the past [11]. Regular physical activity and a healthy and active lifestyle is associated with many health benefits and improved quality of life in patients with congenital heart disease [11]. The intensity of exercise training should be adapted to the specific lesion and physiology [11]. Patients born with CHD are however still over-protected and often restricted from sports, exercise and training [12].

Today's exercise testing is a valuable medical tool in the treatment and diagnosis of pediatric patients with congenital heart disease [6,7,11,13,14, 15]. The assessment of cardiopulmonary fitness and / or its limitation in Fontan patients is important to determine long-term prognosis, detect changes early [16] and to assess response to medical and surgical interventions [11].

The measurement of physical performance provides objective information about the functional status of the heart, lungs and peripheral muscles [16,11]. This information can be useful in clinical decision-making, leading to reduced hospital admissions and improved functional capacity and quality of life [7,11]. Nevertheless, the currently used gold standard, bicycle or treadmill CPET is an expensive, complicated and time-consuming examination, which is therefore often limited to special indications and institutions. It can be carried out as a maximal variant up to complete exertion or submaximal when terminated early [17]. Ovroutski et. al. showed that regular physical monitoring of the exercise capacity of Fontan patients using spiroergometry is essential for the assessment of hemodynamic stability to detect the accurate timing of treatment decisions such as change of medication, re-operation or even thoracic organ transplantation [18].

The 6-minute walking test is another standardized exercise test to assess current fitness and cardiorespiratory status; it is particularly important in everyday clinical practice as it is easy to perform with no equipment needed. Nevertheless, this test is a submaximal test, which only works as a maximal test in patients with severely reduced cardiorespiratory fitness.

Another feature used to assess and evaluate the physical fitness of patients is stair climbing. It is often assessed during the medical history without being objectively reproductive. A standardized stair climb test has previously been evaluated in healthy children as a practical method for assessing physical performance under controlled conditions [19]. Given its simplicity, low cost, and minimal equipment requirements, it represents a potentially valuable alternative or adjunct to traditional cardiopulmonary exercise testing (CPET), especially in settings where CPET is not routinely available [19]. Moreover a lot of studies used a heterogenic version of stair climbing tests (SCT) to assess different body functions. All in all, those protocols lack standardization. They differ in implemention as for instance the total vertical height [20]. In our previous study we assessed the cardiorespiratory fitness in healthy children and adolescents with a standardized SCT and could show a strong correlation to CPET and 6MWT. In the present study, we applied the standardized testing approach to a cohort of patients with Fontan circulation, a population known to exhibit distinct physiological constraints due to the absence of a subpulmonary ventricle and reliance on passive pulmonary blood flow [8]. In contrast to healthy individuals, patients with Fontan circulation often demonstrate **functional limitations**, defined as reduced ability to perform physical tasks due to impaired cardiovascular, pulmonary, or musculoskeletal capacity. These limitations may manifest as reduced exercise tolerance, early fatigue, and diminished peak oxygen uptake, primarily due to chronotropic insufficiency, limited preload, elevated central venous pressure, and reduced cardiac output during exertion [6,11,12,14,18,21,22,]. By evaluating the stair climb test in this unique patient group, we aimed to assess its feasibility, safety, and potential to capture Fontan-specific functional impairments in a simple, clinic-based setting. This could support its future use as a screening tool or follow-up measure in routine care.

Materials and Methods

Ethical statement

The Ethics Committee of the Medical Faculty of the Ludwig-Maximilians University Munich, Munich, Germany, approved this study on the 26.09.2022; it was performed in accordance with the ethical standards of the Declaration of Helsinki. All participants gave their written informed consent to participate in the following study. For minor study participants, prior written informed consent was additionally given from parents.

Study design and study population

This clinical prospective pilot study was conducted at the Department of Pediatric Cardiology and Pediatric Intensive Care Medicine, Ludwig-Maximilians-University Munich. Hemodynamically stable patients with Fontan circulation, female and male between 7 and 29 years of age, who were able to climb stairs on their own, were included. Patients with the following criteria were excluded from the study: sudden cardiac death in the family history, NYHA classification 4, stroke, patients with severe hemiparesis and those with severe

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physical and mental impairment. Subjects were recruited via the department's outpatient clinic. All assessments were completed on the same day under standardized conditions to ensure consistency and minimize external influences. The testing protocol commenced with a comprehensive cardiological evaluation, including echocardiography, measurement of vital parameters (SpO_2, heart rate, and blood pressure), and structured questionnaires addressing medical history, medication use, leisure-time physical activity, and comorbidities. The 6-minute walking test (6MWT) was subsequently performed, followed by a recovery period until vital parameters returned to baseline levels and participants reported subjective recovery. To reduce fatigue-related or warm-up effects, the stair climb test (SCT) was conducted thereafter, with the cardiopulmonary exercise test (CPET) administered last to ensure that peak performance was not biased by prior exertion.

6-Minute Walking Test

The walking distance was measured with the help of the RS PRO Folding measuring wheel and a measured distance between two cones. The test was carried out according to the protocol of the German Association of pediatric cardiology (DGPK) and the American Thoracic Society [34]. Before starting, the instructions were read out loud to the subjects and any ambiguities were clarified. The subject was asked to walk a straight line for 6 minutes as fast as possible without running or jogging, using standardized motivation sentences. At the beginning, the test person had to sit on a chair for about 5 minutes until they reached their resting vital signs. Heart rate, blood pressure and oxygen saturation were recorded using the Connex Spot Monitor (Welch Allyn, Skaneateles Falls, New York, USA,) and noted on the standardized protocol provided. Furthermore, subjects were asked to numerically classify their subjective feeling of exertion and any shortness of breath using the Borg scale and the Borg CR scale. Vital signs and the subjective Borg scale values were repeated after completion of the test.

Stair Climbing Test

Based on the current literature, our SCT protocol includes a minimum of 4 floors of stairs and >12 m of height (total vertical height: 13.14 m, step height: 16.5 cm). The individuals were asked to climb the stairs at their maximum speed up and down. Medical supervision was provided at all times during the test in order to react promptly in case of emergencies. At the beginning, the subject was asked to sit down on a chair and relax. Resting vital signs (blood pressure [BP; mmHg], oxygen saturation [$SpO_{2;}$ %], heartrate [HR; bpm], respiratory rate [RR; 1/min]) were recorded, using the Connex Spot Monitor (Welch Allyn, Chicago, Illinois, USA). The subject had to numerically classify his subjective feeling of exertion and the symptoms of breathlessness using the Borg scale and the Borg CR scale. In addition, a H10 heart rate belt (Polar, Hofheim am Taunus, Germany) was put around the chest of the test person and synchronized with the corresponding app. With this device, the heart rate was measured throughout the test. The subject was then given detailed instructions on the SCT, including the fact that each step should be taken after the other. Subjects were not allowed to hold on to the railing, except in case of emergency. The test was limited by symptoms. Individuals were asked to report any symptoms such as dizziness, palpitation or nausea immediately and to discontinue the SCT if necessary.

To further ensure safety of the patients, each run was accompanied to prevent or catch any falls. Based on the protocol, patients were asked to climb as fast as possible. At the top floor, patients were asked to turn around an immediately climb down the stairs. The time needed to complete this test was recorded. The heart rate at the top of each floor, the maximum heart rate and the time needed to reach the top of each floor was recorded as well as baseline vital signs and Borg scales (Borg scale and Borg CR). After the end of the run and the recording of the above-mentioned vital parameters and scales, subjective complaints and abnormalities during the test were queried and noted.

In order to establish an assessment of the comparability between the CPET, the 6MWT and the SCT, we developed a SCT index for the stair climbing test.

$$SCT\ Index = h[m] \times m\ [kg] / SCT\ time\ [s]$$

m=body weight [kg], h= total vertical height [m], SCT time [s]

Velocity was calculated using the following formula:

$$SCTV\ [m/s] = h\ [m] / SCT\ time\ [s]$$

SCTV [m/s] = velocity, h= total vertical height [m], SCT time [s]

Following this part of the study, the test subjects had a break of at least 30-minute to subjectively fully recover before starting the next exercise test.

Cardio Pulmonary Exercise Testing

Spirometry was performed using the CardioSoft V6.73 program (GE HealthCare, Chicago, Illinois, USA). After completion of the spirometry, a 12-lead ECG was implemented, and a saturation clip was placed on the earlobe. The subject was secured with a safety belt. In addition, a suitable size of breathing mask of the Rudolf type was selected. The subjective Borg scales were then collected. The subject received detailed instructions about the subsequent exercise test and was asked to give a clear stop signal if she or he felt symptoms or maximum exertion and had to stop. The entire spiroergometry was monitored by a medical doctor, who was able to intervene in case of an emergency. The

spiroergometry was performed on the treadmill according to the DGPK protocol [23]. The test was started with a warmup, pre-exercise phase, lasting 90 seconds, at a treadmill speed of 0.8 km/h. The protocol started with a cadence of 2.5 km/h and an incline of 0% at level I. Subsequently, the steps increase by a further 0.5 km/h and 3% gradient every 90 seconds. At load level 8, the treadmill reached its maximum increase of 21%. There was no limit to the increase in speed until the subject stopped. After the test person intended a clear stop signal, a 90-second cool down started with decreasing the incline to 0% and a speed of 0.8 km/h followed by manual control. Particularly in patients with Fontan circulation, attention had to be paid to possible cardiac arrhythmias during the afterload. In addition, a normalization of the heart rate was awaited. After the completion of the cool down, the treadmill was stopped and vitals again documented.

The individual termination criteria and the corresponding Borg scale values were noted at the end of the test. In the 9-field graph according to Wassermann, all important measured variables could be systematically displayed. The averaging of the values was 8 breaths.

Additional relevant parameters that influenced the subsequent evaluation were the maximum heart rate and the percentage of the calculated maximum heart rate that was achieved. The current exercise level with the associated level at termination and the maximum oxygen uptake VO_2max [mL/min/kg], [mL/min], the target value of the maximum oxygen uptake [mL/min], were documented. Blood pressure [mmHg] was measured manually. At the end of CPET, each subject was asked to subjectively rate their exertion and work of breathing using the Borg and Borg CR scales.

Statistical analysis

Statistical analysis was performed using SPSS 27 (Release Date 2020, IBM SPSS Statistics for Windows, version 27.0.1.0, IBM Corp., Armonk, NY, USA) The Kolmogov-Smirnov and Shapiro-Wilk tests were used to assess the normal distribution. Simple correlations were performed using the Spearman rho and Pearson correlation coefficients, depending on whether the correlated variables were normally distributed or not. The significance level was set at $p < 0.05$. We evaluated the correlation between all three forms of exercise testing to see if the SCT is an established method to determine the cardiorespiratory fitness of young patients with Fontan circulation. Therefore, we used our SCT Index and SCT time and correlated it with the most important parameters of the 6MWT and the CPET.

Results

Patients Characteristics

For this study 27 Patients were included, 18 male and 9 female participants. The male participants were on average 18.2 (± 5.7 years) years old and the female participants 18.8 (± 6.9 years). Detailed information on patients' characteristics is summarized in Table 1. Based on the completed questionnaires, patients reported engaging in an average of 2.38 hours of physical activity per week. The physical and medical history revealed comorbidities such as liver stiffness, asthma, epilepsy, protein-losing enteropathy, cyanosis, esophageal varices, celiac disease, arterial hypertension, hypothyroidism, ADHD, history of leukemia, ectopic beats reflecting the complex health profile of the cohort. The study population consisted of patients with various congenital heart defects. Most patients had a New York Heart Association (NYHA) functional classification indicating mild to moderate limitations in physical activity. Medication regimens were highly variable and included anticoagulants, beta-blockers, potassium supplements, cardiac glycosides, and diuretics. One patient had a pacemaker.

Table 1: Patients Characteristics

Variable	N	
Age [years]		
Female	9	18.8 (±6.9)
Male	18	18.2 (±5,7)
<14 years	6	
14-18 years	8	
>18 years	13	
Heart Defects		
Hypoplastic left heart syndrom	22	
Hypoplastic right heart syndrom	2	
Double inlet ventricle	3	
NYHA Classification		
I	8	
II	13	
III	6	
IV	-	
Vitals and Body Measurements		
Resting-HR [bpm]	27	81.67 (± 10.07)
Resting-RR[1/min]	27	18 (14 - 26)
Resting-SBP [mmHg]	27	120.33 (± 10.18)
Resting-DBP [mmHg]	27	75.04 (± 7.75)
Resting SpO_2 [%]	27	92.11 (± 3.18)
BMI [kg/m²]	27	21.07 (± 4.89)
Length [m]	27	1.64 (± 0.18)
Weight [kg]	27	57.82 (± 18.63)
Body Surface [m²]	27	1.64 (0.03 – 2.08)
Waist-Hip-Ratio	25	0.84 (0.67 - 0.99)

BMI=body mass index;SBP=systolic blood pressure;DBP=diastolic blood pressure;HR=heart rate;RR=Respiratory Rate;SpO_2=peripheral capillary oxygen saturation.Data is presented as mean ± SD for normally distributed parameters and as median (IQR) for non-normally distributed parameters

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Results of the 6-Minute Walking Test

Table 2 summarizes all parameters of the 6MWT, pre- and post-testing. On average, the subjects covered a walking distance of 505.17 m (± 112.8 m). The heart rate before the test was 89.56 bpm (± 14.8 bpm) and after the test 111.59 bpm (± 23.8 bpm). The oxygen saturation was 91.67% (± 3.1%) at the beginning and 91.00% (81-96%), after the test so that no relevant drop in saturation could be registered.

Results of the Stair climbing test

26 subjects completed the SCT. One subject was excluded due to bradycardia occurring during the test.

Table 2: Parameters 6-Minute Walking Test

Variable	N	Pre-testing	Post-testing
SBP [mmHg] 6MWT	27	119.7 (± 10.71)	127 (111 - 171)
DBP[mmHg] 6MWT	27	75.41 (± 6.62)	81.26 (± 9.23)
HR[bpm] 6MWT	27	89.56 (± 14.8)	111.59 (± 23.79)
SpO_2 [%] 6MWT	27	91.67 (± 3.15)	91 (81 - 96)
Borg 6MWT	27	6 (6 - 12)	10.89 (± 3.29)
Borg CR 6MWT	27	0 (0 - 2)	2 (0 - 6)
Delta Borg 6MWT	27	-	4.37 (± 3.01)
Delta Borg CR 6MWT	27	-	2 (0 – 5)
Distance 6MWT [m]	27	-	505.17 (± 112.82)

SBP=systolic blood pressure;DBP=diastolic blood pressure;6MWT=6-minute walking test;HR=heart rate;SpO_2=peripheral capillary oxygen saturation.Data is presented as mean ± SD for normally distributed parameters and as median (IQR) for non-normally distributed parameters

The average SCT time needed was 61.55 seconds [43.90-179.00]. The subjects achieved an average maximum heart rate of 167.46 bpm (± 21.04 bpm). At the end of the SCT, a slight decrease in peripheral oxygen saturation (SpO_2) was observed, subjects had an oxygen saturation of 89.5% [81-96] compared to the beginning of 92.54% (± 3.24%). The respiratory rate increased to 39.69/min (± 7.85/min). All relevant parameters are listed in Table 3.

Results of the Spiroergometry

Table 4 outlines the relevant CPET parameters according to their distribution. On average, the respiratory coefficient RQ was 1.19 (± 0.17), ensuring maximum exertion. The VO_2max [mL/min/kg] was 29.77 [mL/min/kg] (± 8.17 mL/kg/min). The subjects achieved an average of 72.16 % (± 19.79 %) of the target value for VO_2max [mL/min] of healthy individuals. The maximum O2 pulse was 9.75 mL (± 3.08 mL).

Correlation Analysis

We evaluated the correlation between all three forms of exercise testing to see if the SCT is an established method to determine the cardiorespiratory fitness of young Fontan patients. Therefore, we used our SCT index and the SCT time and correlated it with the most important parameters of the 6MWT and the CPET. One adolescent was excluded due to exercise-induced bradycardia.

Table 3: Parameters Stair Climbing Test

Variable	N	Pre-testing	Post-testing
SCT Time [s]	26	-	61.55 (43.9 - 179)
SCT Index	26	-	11.18 (±5.15)
SCTV [m/s]	26	-	0.194(± 0.07)
HRmax SCT	26	-	167.46 (± 21.04)
HR [bpm] SCT	26	87.04 (± 14.87)	153 (± 22.97)
RR [1/min] SCT	26	19 (14 - 26)	39.69 (± 7.85)
SpO_2 [%] SCT	26	92.54 (± 3.24)	89.5 (81 - 96)
SBP [mmHg] SCT	26	121 (107 - 166)	142.69 (± 22.33)
DBP [mmHg] SCT	26	78.38 (± 8.67)	83.12 (± 10.27)
Delta Borg SCT	26	-	7.62 (± 3.74)
Delta Borg CR SCT	26	-	5.06 (± 3.07)

SCT=stair climbing test;SCTV=velocity stair climbing test;HR=heart rate;RR=respiratory rate;SBP=systolic blood pressure;DBP=diastolic blood pressure;SpO_2=peripheral capillary oxygen saturation.Data is presented as mean ± SD for normally distributed parameters and as median (IQR) for non-normally distributed parameters

Table 4: Parameters Spiroergometry

Variable	N	
RQ	27	1.19 (± 0.17)
Vmax[km/h]	26	5.16 (± 0.68)
VO_2max [mL/min/kg]	27	29.77 (± 8.17)
VO_2max [mL/min]	27	1642.85 (± 562.75)
VO_2 Target value	27	2361.44 (± 762.97)
VO_2 Target value %	27	72.16 (± 19.79)
HR max [bpm]	27	178.63 (± 21.62)
Level max	27	6 (± 1.39)
Exposure Time [mm:ss]	27	8.31 (± 1.99)
Delta Borg	27	11 (3 - 14)
Delta Borg CR	27	6.72 (± 2.4)
O2pulse [mL]	27	9.75 (± 3.08)

RQ=respiratory quotient;Vmax=maximal speed;VO_2max=maximal O2 uptake;HR=heart rate;O2pulse=oxygenpulse.Data is presented as mean ± SD for normally distributed parameters and as median (IQR) for non-normally distributed parameters

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Table 5: Correlation Analysis between the SCT index, SCT time and parameters of the 6MWT and the CPET

Variable	N	SCT index		SCT time [s]	
		r	*p*-Value	r	*p*-Value
Distance 6MWT [m]	26	0.423*	0.031	-.608**	0.001
VO_2max [mL/min/kg]	26	0.305	0.130	-.650**	< 0.0001
VO_2max [mL/min]	26	0.808**	< 0.0001	-0.488	0.011
O2 pulse [mL]	26	0.723**	< 0.0001	-0.351	0.079

SCT=stair climbing test; 6MW=6-minute walking test; VO_2max=maximal O2 uptake

We found a strong correlation between the walked distance in the 6MWT and the SCT index r = 0.423 (p= 0.031) and a significant p<0.0001 correlation between the two main parameters of the CPET, VO_2max and O2 pulse and our SCT index as seen in Table 5 and Figure 1 and 2.

All observed associations between SCT completion time and measures of the 6MWT and cardiopulmonary function are summarized in Table 5. SCT completion time was inversely associated with six-minute walk distance in the overall cohorts, and negatively related to relative maximal oxygen uptake, indicating that longer completion times reflect lower functional capacity and cardiopulmonary performance, as illustrated in Figures 3 and 4.

SCT velocity was positively associated with measures of functional capacity and cardiopulmonary performance in the overall cohort. Faster SCT velocity reflected higher submaximal functional mobility, greater maximal oxygen uptake, and improved cardiovascular efficiency. These associations are summarized in Table 6 and illustrated in Figures 5 and 6.

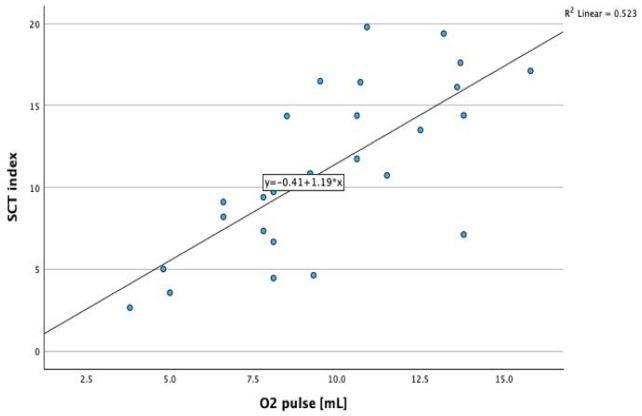


Figure 1: Correlation of SCT index to O2 pulse[mL] (r=0.723; p<0.0001)

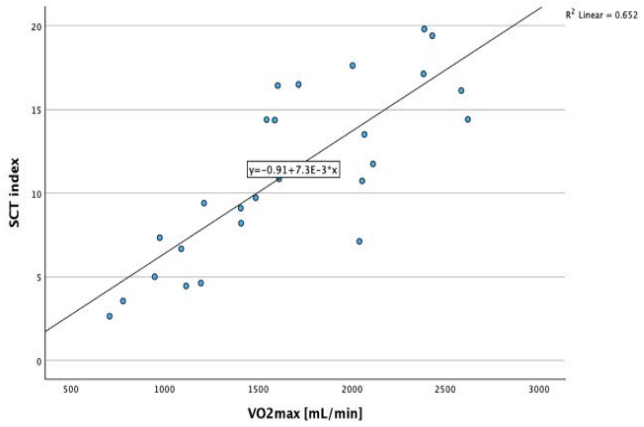


Figure 2: Correlation of SCT index toVO2max [mL/min] (r=0.808; p<0.0001)

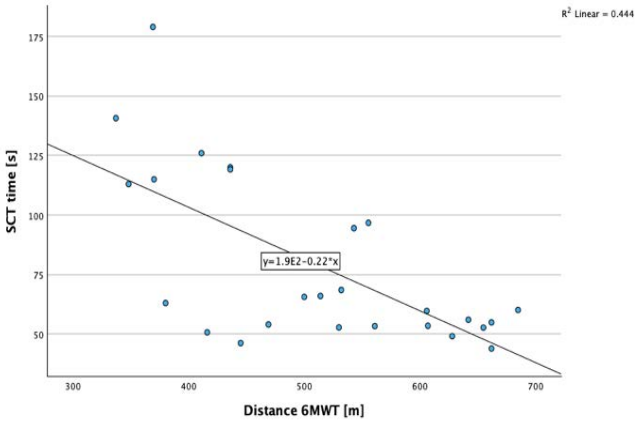


Figure 3: Correlation of the SCTt to the 6MWD (r=-0.608; p=0.001)

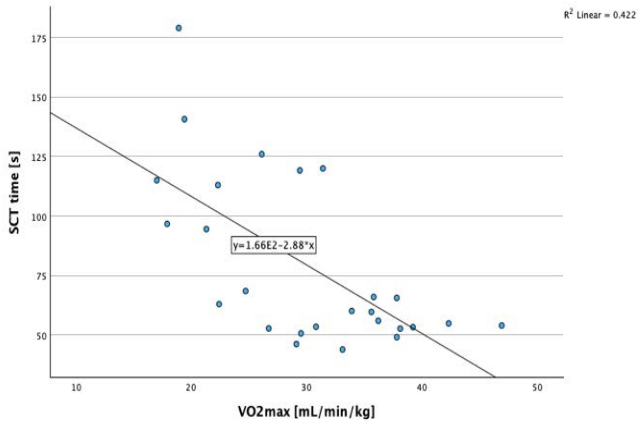


Figure 4: Correlation of the SCTt to the VO2max[mL/min/kg] (r=-0.650; p<0.0001)

Table 7 demonstrate the association between physiological responses in the SCT and the CPET by a correlation analysis using the peak heart rates achieved during both assessments. The analysis showed a significant correlation indicating a meaningful concordance in cardiovascular strain across the two protocols, as illustrated in **Figure 7.**

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In addition, we analyzed maximal oxygen uptake in relation to six-minute walk distance to investigate potential associations between aerobic capacity and submaximal functional performance. Figure 8 illustrate this correlation.

Table 6: Correlation Analysis between the SCT velocity and parameters of the 6MWT and the CPET

Variable	N	SCTV	
		r	*p-Value*
Distance 6MWT [m]	26	0.645**	< 0.0001
VO_2max [mL/min/kg]	26	0.654**	< 0.0001
VO_2max [mL/min]	26	0.502**	0.009
O2 pulse [mL]	26	0.345	0.084

SCTV=stair climbing velocity;6MWT= 6-minute walking test;CPET= cardiopulmonary exercice testing;VO_2max=maximal O2 uptake

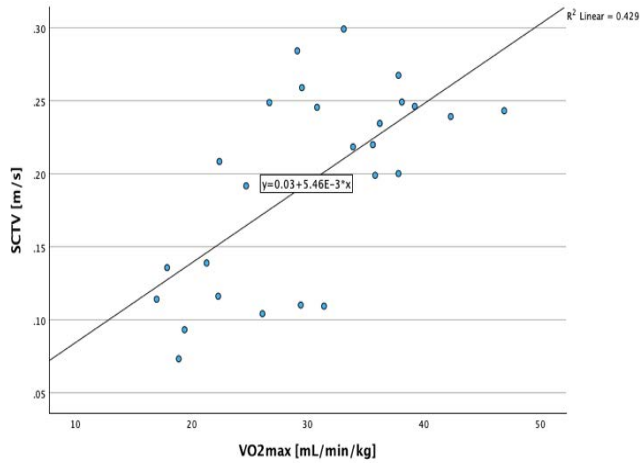


Figure 5: Correlation SCTV to VO2max[mL/min/kg] (r=0.654; p<0.0001)

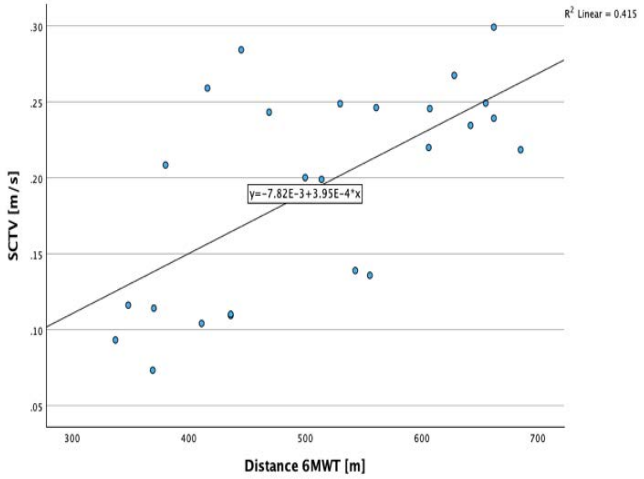


Figure 6: Correlation SCTV to 6MWD(r=0.645; p<0.0001)

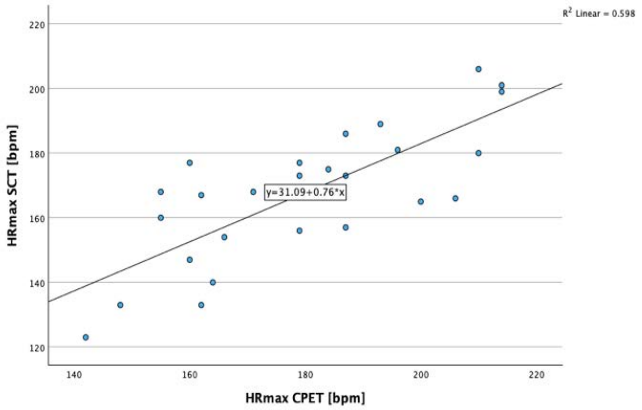


Figure 7: Correlation HRmax SCT to HRmax CPET (r=0.773; p<0.0001).

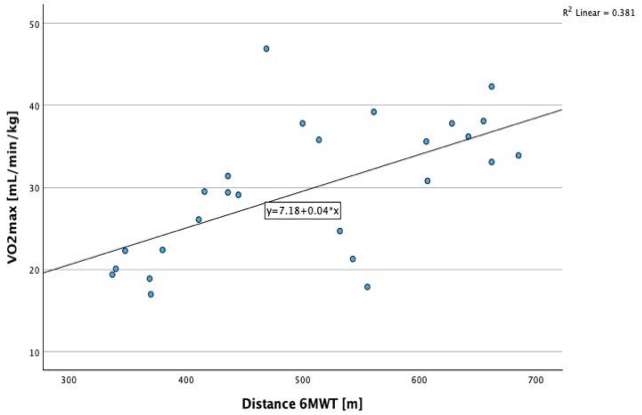


Figure 8: Correlation 6MWD to VO2max[mL/min/kg] (r=0.454;p<0.05)

Discussion

As demonstrated in our previous study, we were able to establish a significant correlation between our Stair Climbing Test (SCT) protocol, the 6-minute walk test (6MWT), and the cardiopulmonary exercise test (CPET) in healthy children and adolescents [19]. While this was an important first step to validate the SCT in a healthy pediatric population, the specific physiological conditions and exercise limitations of patients with Fontan circulation necessitated a separate investigation.

Patients with Fontan circulation represent a unique cohort with distinct hemodynamic characteristics. They have a single ventricle, passive lung perfusion, and a failing or inadequate increase in venous return, resulting in reduced preload and an inability to increase stroke volume during exercise [8]. This leads to a reduced oxygen uptake (VO_2) at peak exercise (VO_2max), an inadequate increase in cardiac output during exercise, and therefore limited exercise tolerance [6,11,14,21].

While chronotropic incompetence, characterized by a reduced peak heart rate (HRmax), has been reported in patients

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with Fontan circulation and is considered a contributing factor to reduced exercise capacity[11,18,22],this finding was not consistently observed in our cohort.

Notably, pediatric participants under 14 years of age appeared less affected, which may be attributable to age-related differences in autonomic regulation, greater physiological heart rate reserves, and heterogeneous stages of cardiovascular adaptation.

Other factors contributing to reduced exercise capacity include systolic and diastolic ventricular dysfunction, and arterial stiffness—all commonly seen in Fontan patients [6,12]. Consequently, their expected performance in exercise testing differs markedly from that of healthy peers. This pathophysiology outlines the importance of regular assessment of exercise capacity in Fontan patients.

To establish the SCT's validity as a marker of cardiorespiratory fitness in patients with Fontan circulation, we first analyzed established maximal (CPET) and submaximal (6MWT) exercise tests in our cohort. These served as benchmarks to which SCT outcomes could be compared. While submaximal tests like the 6MWT are useful in more severely impaired individuals, maximal tests like the CPET are preferable in most other scenarios. Our newly developed SCT may serve as a safe, quick, reliable, and easy-to-perform maximal test to evaluate cardiorespiratory fitness in this unique patient group.

In contrast to healthy children, who typically achieve higher VO_2max values as shown in our prior study [19], patients with Fontan circulation generally display significantly reduced exercise capacity, which decreases further with age [8]. In our current study, we demonstrated that Fontan subjects achieved an average VO_2max [mL/min/kg] of 29.77 (± 8.17) during CPET, which corresponds to approximately 72.16% of the predicted value for healthy individuals. According to the literature, our results are within the age-appropriate reference range for patients with Fontan circulation [18,24]. Ovroutski et al. reported a significant decline in VO_2max between early and late postoperative testing in 43 patients with univentricular hearts post-total cavopulmonary connection (TCPC), showing a decrease from 26.5 (13.9–44) to 20.7 (10.3–39) mL/kg/min,$p< 0.001$ [18]. Similarly, Müller et al. showed that patients with Fontan circulation after TCPC exhibited physical performance levels at approximately 60% of predicted values [25].

As part of the CPET evaluation, we also examined secondary cardiopulmonary variables such as O2 pulse, which provide additional insight into stroke volume and peripheral oxygen extraction. Bansal et al. investigated 44 Fontan patients and 85 healthy controls using CPET. The mean maximal O2 pulse in the Fontan group was 9.80 mL/beat (± 4.11), compared to 13.63 mL/beat (± 4.7) in controls ($p < 0.01$) [26]. Our study found comparable results, with a mean O2 pulse of 9.75 mL/beat (±3.08). Harteveld et al. further supported this observation, reporting a 59% reduction in O2 pulse in patients with Fontan circulation ($p < 0.001$), potentially due to decreased stroke volume [6]. Groepenhoff et al. found that in patients with pulmonary hypertension, O2 pulse added modest prognostic value to the 6MWT [27]. In our data, the correlation between O2 pulse and 6MWT distance was weak ($r = 0.244$) and not statistically significant.

Compared to the healthy population, patients with Fontan circulation also exhibited a reduced maximum heart rate (HRmax) during treadmill and cycle ergometer exercise tests, with a median reduction of 5%. This was observed across different age groups and postoperative stages [11,18]. We found similar results in our study.

Although VO_2max remains a key prognostic marker in many cardiovascular conditions, it requires maximal exertion [28]. Terol et al. showed that submaximal testing is comparably predictive of exercise capacity in young Fontan patients and noted a decline in VO_2peak% over time [28].

In our analysis, we found a significant correlation between SCT performance (time and speed) and VO_2max[mL/min/kg] during CPET. The SCT Index also correlated significantly with VO_2max [mL/min], supporting the reliability of SCT as a surrogate marker of exercise capacity. These results are particularly relevant as the SCT provides a feasible, less resource-intensive option for evaluating functional capacity in this vulnerable population. While our previous study validated the SCT in healthy subjects with expected normal responses to exertion [19], the current study confirms its applicability in Fontan patients, who are likely to demonstrate reduced chronotropic and inotropic reserve.

In addition to the CPET, we assessed submaximal performance using the 6-minute walk test (6MWT). This well-established method complements maximal testing by capturing functional capacity in more impaired individuals and serves as a second reference point against which SCT results can be evaluated. Agarwala et al. described the 6MWT as a widely accepted test for assessing exercise capacity in patients with moderate to severe pulmonary disease. It is cost-effective and requires no sophisticated equipment [29]. Its application in children with congenital heart disease has been validated for assessment and follow-up in rehabilitation settings [13]. It is especially suitable for severely impaired patients or those unable to perform treadmill or cycle ergometry [30]. However, the 6MWT is not designed to identify the underlying cause of exercise limitation [30]. Ulrich et al. studied 496 healthy children (mean age 11.1 ± 3.4 years) and found an average walking distance of 618 ± 79 meters. While weight and height increased steadily with age, the distance plateaued after puberty [31]. In our Fontan

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cohort, the mean 6MWT distance was 505.17 m (± 112.8 m), aligning with findings by Ampuero et al., who reported a mean of 551.3 meters (84% of the predicted distance) in patients with Fontan circulation aged 6–16 years [13]. Therefore, to assess the SCT's clinical utility, we analyzed its relationship 6MWT outcomes. Specifically, we examined correlations between SCT performance metrics (time, speed, SCT Index) and 6MWT distance. Significant correlations were observed for all three SCT variables with 6MWT distance. Thus, our data suggest that, with certain limitations, the SCT may be a suitable alternative to the 6MWT for assessing cardiorespiratory fitness in this population. The stair climbing test may better reveal functional limitations than the six-minute walk test because it imposes a higher physiological demand in a shorter period of time. While the 6MWT primarily assesses submaximal endurance, the SCT challenges both cardiovascular and musculoskeletal systems more intensively, potentially unmasking deficits that remain undetected during lower-intensity tests. This higher exertion could make subtle functional impairments more apparent, particularly in populations with congenital heart defects or limited cardiopulmonary reserve.

Furthermore, we observed a strong correlation ($r=0.617$; $p<0.01$) between VO_2max and 6MWT distance, consistent with prior studies [13,32]. Niedeggen et al. also found a significant correlation between brain natriuretic peptide levels, VO2peak, and 6MWT distance, although not with VO_2 at the anaerobic threshold [32].

In summary, while the SCT has already been validated in healthy pediatric cohorts, this study extends its application to Fontan patients, who represent a clinically distinct group with unique physiological limitations and exercise profiles. This distinction justifies the need for a separate evaluation and highlights the SCT as a practical, reliable, and valuable tool in the clinical management of Fontan circulation.

Strenght and Limitations

As our study is a pilot study, the data naturally only relate to a small cohort and may need confirmation on a larger scale. As shown in other studies, the SCT can be used in different subject groups to assess the CRF [19,33].

The SCT provides a solid basis for the assessment of patients with Fontan circulation, especially in children and adolescents who are either too anxious for treadmill/bicycle ergometry or who do not have timely availability and trained personnel for CPET. According to Dold et al., regular physical activity and exercise are encouraged in children with congenital heart disease to preserve motor skills and functional capacity [12]. In line with these recommendations, our cohort reported an average of 2.28 hours of sports participation per week, and no relevant deficits in coordination or leg strength were observed. Moreover, the coordination required for stair climbing is, from a motor perspective, superior to that of running or cycling, as it combines muscle strength during ascent with coordination during descent. Since almost all children and adolescents are accustomed to stair climbing in everyday life, the movements performed are familiar and reproducible, thereby allowing precise and ecologically valid conclusions about daily functional performance.

Furthermore, it is a simple, cost- and time-efficient method to evaluate the cardiorespiratory fitness in daily life.

In our study, we were able to show that young univentricular patients were able to exert themselves maximally, which qualifies the SCT as a maximal exercise test alongside the CPET.

Despite the ease with which it can be performed and its informative value in terms of physical performance, the limitations of SCT should be recognized. Therefore, whenever there is need for more detailed diagnostics, particularly for the assessment of lung function CPET should be added, as spiroergometry certainly provides more and more precise physiological measurement variables, which may better reflect a subtle change in the status of the patient's individual exercise capacity, especially in patients with relatively preserved exercise capacity [30].

Further consideration should be given on the fact that there is no continuous ECG during SCT. In patients looking for possible cardiac arrhythmias, continuous ECG monitoring may be added. Furthermore, i.e. your own motivation to climb stairs makes a significant contribution to the time required and therefore to the final results. This should not be neglected, especially in children and adolescents, as there can be major differences, particularly in the corresponding age categories.

It should be noted that there are no special safety precautions for SCT with regard to possible falls. The CPET is therefore superior to the SCT in terms of patient safety due to the attached safety harness. Especially in patients with Fontan circulation who might suffer from hemiparesis due to thromboembolic events, climbing stairs is a challenge and a potential danger in terms of falls.

It is important to acknowledge that the performance of children and adolescents in exercise testing can be substantially influenced by motivational factors. To minimize variability due to inconsistent encouragement, all participants in our study received standardized verbal prompts during both the SCT and CPET, using identical phrasing for each subject. This approach ensured a uniform level of external motivation across tests. For the 6MWT, motivational input is inherently standardized, as the use of fixed instructions and prompts is mandated by established test protocols. The American

Thoracic Society (ATS) guidelines recommend performing at least two six-minute walk tests because of the considerable learning effect observed in pediatric and cardiac populations. The lack of repeated testing in our study therefore represents a potential limitation [34].

Conclusions

We could demonstrate a good correlation between the SCT and CPET and 6MWT. We therefore can conclude that the SCT is a solid, meaningful exercise test that is easy to use in everyday life in young patients with Fontan circulation. By correlating the parameters of spiroergometry such as VO_2max and O2 pulse with the main parameters of the SCT, we were able to prove that the SCT is a reliable alternative to spiroergometry in patients with Fontan circulation with regard to their maximum exercise capacity and thus their assessment of physical performance. The coordination required when climbing stairs is more challenging as running or cycling. Climbing stairs involves a combination of muscle strength (upwards) and coordination (downwards). Almost every child or adolescent is used to climbing stairs in everyday life, so the required movements and the sequence of actions are identical to those in everyday life, which in turn allows precise and accurate conclusions to be drawn about everyday performance.

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