# Treadmill Testing of Children Who Have Spina Bifida and Are Ambulatory: Does Peak Oxygen Uptake Reflect Maximum Oxygen Uptake?

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**Background.** Earlier studies have demonstrated low peak oxygen uptake ($\dot{V}O_2$peak) in children with spina bifida. Low peak heart rate and low peak respiratory exchange ratio in these studies raised questions regarding the true maximal character of $\dot{V}O_2$peak values obtained with treadmill testing.

**Objective.** The aim of this study was to determine whether the $\dot{V}O_2$peak measured during an incremental treadmill test is a true reflection of the maximum oxygen uptake ($\dot{V}O_2$max) in children who have spina bifida and are ambulatory.

**Design.** A cross-sectional design was used for this study.

**Methods.** Twenty children who had spina bifida and were ambulatory participated. The $\dot{V}O_2$peak was measured during a graded treadmill exercise test. The validity of $\dot{V}O_2$peak measurements was evaluated by use of previously described guidelines for maximum exercise testing in children who are healthy, as well as differences between $\dot{V}O_2$peak and $\dot{V}O_2$ during a supramaximal protocol ($\dot{V}O_2$supramaximal).

**Results.** The average values for $\dot{V}O_2$peak and normalized $\dot{V}O_2$peak were, respectively, 1.23 L/min (SD=0.6) and 34.1 mL/kg/min (SD=8.3). Fifteen children met at least 2 of the 3 previously described criteria; one child failed to meet any criteria. Although there were no significant differences between $\dot{V}O_2$peak and $\dot{V}O_2$supramaximal, 5 children did show improvement during supramaximal testing.

**Limitations.** These results apply to children who have spina bifida and are at least community ambulatory.

**Conclusions.** The $\dot{V}O_2$peak measured during an incremental treadmill test seems to reflect the true $\dot{V}O_2$max in children who have spina bifida and are ambulatory, validating the use of a treadmill test for these children. When confirmation of maximal effort is needed, the addition of supramaximal testing of children with disability is an easy and well-tolerated method.

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Because of advances in medical science, many children with chronic diseases now have longer and healthier lives. This change requires a different approach in the medical management of these patients from childhood through adolescence and into adulthood. An approach that focuses not only on the pathological aspects but also on the (preventable) medical, functional, and social consequences of the disease and lifestyle issues is needed. As a result of this shift, exercise testing and training in children with chronic diseases, such as spina bifida, have emerged as areas of interest in the field of pediatric exercise physiology.[1]

Spina bifida is the most frequent congenital deformity of the neural tube, with an incidence of 0.4 to 1.0 per 1,000 births.[2–4] Depending on both the type and the level of the spina bifida lesion, patients can experience a variety of deficits in cognition, motor function, sensory function, and bowel and bladder function.[5] Besides medical classification according to type, lesion level, and presence of hydrocephalus, children are functionally classified as having "normal ambulation" or "community ambulation" by use of the adapted Hoffer classification.[6,7] Appendix 1 provides descriptions of ambulation levels.

About 20% of lesions occur at the sacral level, enabling most children so affected to have community or normal ambulation. Despite high levels of functioning, these patients still experience difficulties in performing both dynamic motor skills and activities of daily living.[8] This situation could be an important factor in inducing a cycle of less ability resulting in less activity, further reducing physical fitness and ambulation. Studies have indeed shown children and young adults with spina bifida to be less active and to have lower levels of physical fitness than their peers who are healthy.[9–12]

In exercise testing, maximum oxygen uptake ($\dot{V}O_2max$ [Appendix 2]) is considered to be the single best indicator of aerobic exercise capacity, which often is referred to as "aerobic fitness."[13] Gas exchange analysis during an incremental ergometry test to the point of volitional termination because of exhaustion is considered the gold standard for measuring $\dot{V}O_2max$.[14] There has been much debate about peak oxygen uptake ($\dot{V}O_2peak$) [Appendix 2]) versus $\dot{V}O_2max$. Whereas $\dot{V}O_2peak$ is the highest level of oxygen uptake ($\dot{V}O_2$ [Appendix 2]) attained during a single test, $\dot{V}O_2max$ is considered to be the maximum possible attainable level of oxygen utilization by both the cardiorespiratory and the neuromuscular systems, resulting in a $\dot{V}O_2$ plateau at the end of testing despite an increase in workload.[15,16]

A common method of exercise testing in children is incremental cycle or treadmill testing.[1] In patients with spinal cord disease or dysfunction (including spinal cord injury and spina bifida)[17] and in patients with spina bifida,[18] arm ergometry has been used. An advantage of using arm ergometry with this population could be that the muscles tested are less involved in the disease process. In this way, the outcomes of the test might more closely reflect cardiorespiratory limitations in exercise testing. On the other hand, upper-extremity ergometry has been known to result in lower $\dot{V}O_2peak$ values because of the smaller muscle mass involved in testing.[19] At the same time, for this group of children, ambulation is the main mode of transportation. In this case, it is recommended that a treadmill be used for maximum exercise testing because of its specificity.[20–22]

To evaluate whether an exercise test in children yields "true" maximum values, Bar-Or and Rowland[1] described guidelines regarding heart rate (HR [Appendix 2]), respiratory exchange ratio (RER [Appendix 2]), and the presence of a $\dot{V}O_2$ plateau in the final minutes of testing. Because the presence of a plateau in both adult and pediatric exercise testing has been disputed,[13] supramaximal protocols, such as the one-session protocol described by Rossiter et al,[16] have been used to evaluate whether the added step can yield higher $\dot{V}O_2$ values. When the supramaximal step does not result in increased $\dot{V}O_2$, $\dot{V}O_2peak$ is considered to be a valid indicator of $\dot{V}O_2max$.

In an earlier study,[23] we reported a reduction in $\dot{V}O_2peak$ values when a treadmill exercise test was used for children who had spina bifida and were ambulatory. The lower $\dot{V}O_2peak$ values in that study seemed to be attributable to reduced muscle mass, deconditioning, and possible ventilatory limitations. In addition, both low peak HR (HRpeak) and low peak RER (RERpeak) in both our study and the literature[11,23,24] raised questions regarding the true maximal character of $\dot{V}O_2peak$ values obtained with this mode of testing.

Although earlier studies of treadmill exercise testing of children who were healthy showed that it is possible to validly test $\dot{V}O_2peak$ in children who are healthy,[25–29] no research has been done on the validity of $\dot{V}O_2peak$ testing in children who have spina bifida and are ambulatory. The purpose of this study, therefore, was to determine whether $\dot{V}O_2peak$ measured during a graded treadmill exercise test reflects $\dot{V}O_2max$ in children who have spina bifida and are ambulatory.

## Method

### Participants

This study was part of a larger study regarding exercise and functional capacity testing of children who were diagnosed with spina bifida (the Utrecht Spina Bifida And Graded Exercise [USAGE] study) and were ambulatory. Study procedures took place at the Department of Pediatric Physical Therapy and Exercise Physiology, Wilhelmina Children's Hospital, University Medical Center Utrecht, Utrecht, the Netherlands, in 2007 and 2008.

Children were included when they had at least community ambulation, were able to follow instructions regarding testing, and were between 6 and 18 years of age. Parents and children signed informed consent statements before testing. Exclusion criteria were medical events that might interfere with the outcomes of the testing or medical status that did not allow maximum exercise testing. The power calculation was performed with the assumption of an alpha value of .05 and a power of 80%. On the basis of population mean and standard deviation values of 33.14 and 7.6, respectively, for $\dot{V}O_2$peak/kg/min[23] and with the assumption of a correlation of .9, a sample size of 18 children was determined to be sufficient to detect differences during the supramaximal step of testing at 110% of the maximum achieved speed.[30]

The study population consisted of 20 children who had spina bifida and were ambulatory (9 boys and 11 girls). The level of the lesion (classified according to the guidelines of the American Spinal Injury Association[31]), the ambulation level, Six-Minute Walk Test (6MWT) results, age, and anthropometric measurements are shown in Table 1.

**Table 1.**
Level of Lesion and Functional Ambulation Level in Groups of Children

| Parameter[a] | No. (%) of Children | | |
|---|---|---|---|
| | All (n=20) | With Normal Ambulation (n=10) | With Community Ambulation (n=10) |
| Level of lesion | | | |
| L3–L4 | 2 (10) | 0 (0) | 2 (20) |
| L4–L5 | 7 (35) | 1 (10) | 6 (60) |
| L5–S1 | 6 (30) | 4 (40) | 2 (20) |
| S2 and below | 1 (5) | 1 (10) | 0 (0) |
| No motor loss | 4 (20) | 4 (40) | 0 (0) |
| 6MWT | | | |
| Walking >400 m | 13 (65) | 9 (90) | 3 (30) |
| Distance walked, m, $\bar{X}$ (SD) | 418 (95) | 473 (45.5) | 357 (100)[b] |
| Anthropometric measurements, $\bar{X}$ (SD) | | | |
| Age | 10.3 (4.9) | 9.9 (3.2) | 11.1 (4.1) |
| Height, m | 1.36 (0.21) | 1.38 (0.19) | 1.32 (0.24) |
| Weight, kg | 37.1 (18.7) | 35.9 (15.0) | 38.2 (21.5) |
| BMI, kg/m² | 18.9 (3.9) | 17.8 (2.8) | 20.1 (4.7) |

[a] 6MWT=Six-Minute Walk Test, BMI=body mass index.
[b] $P<.05$ for difference between children with normal ambulation and children with community ambulation.

### Demographics

Data concerning medical history were obtained from medical records. These data included the type of spina bifida, the level of the lesion, the ambulation level, age, and sex.

### Body Mass Index

The body mass index was calculated as weight (kilograms) divided by height squared (meters squared). This index has proven to be a reliable and valid tool for estimating children's nutritional status (such as whether they are overweight or underweight).[32,33] Weight was measured with an electronic scale. Height was measured with a wall-mounted centimeter scale.

### Peak Oxygen Uptake and Supramaximal Oxygen Uptake

In previous studies, treadmill protocols were used to test $\dot{V}O_2$peak in children with disability,[11,34,35] including children with spina bifida.[11,23] In the present study, $\dot{V}O_2$peak was measured with a graded treadmill (EnMill*) test because all children should have been able to perform this test and because reference values are available for both young children and adolescents. To accommodate children with different ambulatory abilities, we used 2 progressive exercise test protocols. Children ambulating less than 400 m during the 6MWT were tested with a starting speed of 2 km/h, which was gradually increased by 0.25 km/h every minute, with a set grade of 2%. Children ambulating farther than 400 m during the 6MWT were tested with a starting speed of 3 km/h, which was increased by 0.50 km/h every minute, with a set grade of 2%. The cutoff point of 400 m was chosen on the basis of earlier testing in our labora-

* Enraf, Delft Techpark 39, 2628 XJ Delft, the Netherlands.

**Table 2.**
Rowland Criteria Used to Evaluate Peak Oxygen Uptake in Children Who Are Healthy

| Criteria | Description |
|---|---|
| Subjective[a] | Unsteady walking, running, or biking |
| | Sweating |
| | Facial flushing |
| | Clear unwillingness to continue despite encouragement |
| Objective | Heart rate of >95% (210 − age) |
| | Respiratory exchange ratio of >1.00 |
| | Oxygen uptake plateau in last minute |

[a] Signs of intense effort.

tory.[21,22] The children were allowed to use handrails to maintain balance. The protocols were continued until the children stopped because of exhaustion, despite verbal encouragement from the test leader.

After a resting period of 4 minutes, the children were tested for a maximum of 3 minutes at 110% of their maximum achieved speed. This type of supramaximal testing for adults who were healthy was described by Rossiter et al.[16]

During the incremental exercise testing, physiologic responses, including breath-by-breath gas analysis, were measured with an HR monitor (Polar Accurex[†]) and a calibrated mobile gas analysis system (Cortex Metamax B[3‡]). The Cortex Metamax is a valid and reliable system for measuring gas exchange parameters during exercise.[36,37]

## Ambulatory Ability

Ambulatory ability was measured during the 6MWT. The test was performed on a 20-m track in a straight corridor. The children were instructed to cover the greatest possible distance in 6 minutes at a self-selected walking speed. The test and encouragements during the test were in accordance with the guidelines of the American Thoracic Society.[38] The walking distance in the 6MWT was recorded in meters. This test was performed before the treadmill test and was followed by a 15-minute recovery period.

[†] Polar-Nederland BV, Antennestraat 46, 1322 AS Almere, the Netherlands.
[‡] Cortex Medical GmbH, Nonnenstrasse 39, Leipzig, Germany.

## Data Analysis

**$\dot{V}O_2$peak.** Both peak and supramaximal exercise parameters were calculated as average values during the last 30 seconds of the exercise test. Normalized $\dot{V}O_2$ was calculated as $\dot{V}O_2$peak/kg or $\dot{V}O_2$supramaximal/kg and was expressed as milliliters per kilogram per minute. Two-tailed *t* tests were used to test differences between children with community ambulation and children with normal ambulation after testing for normal distribution and equality of means. The significance level was set at a *P* value of less than .05. To evaluate the validity of maximum exercise testing in children with spina bifida, we analyzed the data with the following methods.

**Rowland criteria.** Rowland established criteria for maximum exercise testing in children who are healthy.[39] These criteria are subdivided into subjective (ie, qualitative) and objective (ie, quantitative) criteria; a child has to meet the subjective criteria and at least 2 of the objective criteria for the test to be considered of maximal effort and character (Tab. 2). The $\dot{V}O_2$ plateau was determined from the difference between normalized $\dot{V}O_2$peak and $\dot{V}O_2$ in the last 30 seconds of the minute before the last minute. When the difference was 2.1 mL/kg/min or less, the child was considered to have reached a plateau.[40]

**Supramaximal protocol.** Two-tailed paired *t* tests were used to test differences between normalized $\dot{V}O_2$peak and $\dot{V}O_2$supramaximal after testing for normal distribution and equality of means. The significance level was set at a *P* value of less than .05. Statistical analyses were performed with SPSS for Windows (version 15.0).[§] Clinically relevant differences between normalized $\dot{V}O_2$peak and $\dot{V}O_2$supramaximal were defined as those for a plateau at greater than 2.1 mL/kg/min, as stated above.

# Results

## Exercise Testing

Twenty children completed the graded treadmill exercise test followed by a 3-minute supramaximal test. The supramaximal protocol was well tolerated. Only one child (subject 17) was not able to complete the full 3 minutes of supramaximal testing and had to stop after 2 minutes. The $\dot{V}O_2$peak, HRpeak, peak ventilation, peak carbon dioxide exhaled, and RERpeak are shown in Table 3 (see also Appendix 2). The $\dot{V}O_2$peak and $\dot{V}O_2$peak/kg values averaged 1.23 L/min (SD=0.6) and 34.1 mL/kg/min (SD=8.3), respectively.

## Rowland Criteria

All children showed signs of the subjective criteria. Sixty-five percent of the children reached a $\dot{V}O_2$ plateau during the last minute of exercise testing. The criteria for HRpeak were met by 65% of the children, whereas 80% reached an RERpeak of greater than 1.00. Seven children met all 3

[§] SPSS Inc, 233 S Wacker Dr, Chicago, IL 60606.

criteria, 8 children met 2 criteria, and 4 children met one criterion; one child failed to meet any criteria (Tabs. 4 and 5). Seventy-five percent of the children met at least 2 of the 3 criteria.

## Supramaximal Protocol

No significant differences were seen between the regular test and the supramaximal protocol ($\dot{V}O_2$peak versus $\dot{V}O_2$supramaximal: 34.1 versus 34.8 mL/kg/min; $P$=.274). Individual differences are shown in Table 5. An example of $\dot{V}O_2$peak and $\dot{V}O_2$supramaximal testing is shown in the Figure.

As indicated by the individual values, 5 children showed clinically relevant differences between normalized $\dot{V}O_2$peak and $\dot{V}O_2$supramaximal. The $\dot{V}O_2$ increased by more than 2.1 mL/kg/min during supramaximal testing in these children. The $\dot{V}O_2$ did not increase during supramaximal testing in the other children; 10 children were not even able to reach previous peak values despite an increase in speed.

Of the 5 children who did not meet at least 2 of the 3 objective criteria described by Rowland,[39] 2 continued to improve during supramaximal testing. The child who failed to meet any criteria (subject 1) did not show an improvement in $\dot{V}O_2$ during the added step. Of the children who showed an increase in $\dot{V}O_2$ during supramaximal testing, one child had met all 3 criteria (subject 8), 3 children had met 2 of the 3 criteria (subjects 4, 7, and 16), and one child (subject 3) had met only one of the criteria for maximum exercise testing. Three children did not meet the HRpeak criteria (subjects 3, 7, and 16), one child reached an RERpeak of less than 1.00 (subject 4), and one child did not reach a $\dot{V}O_2$ plateau in the last minute of exercise testing. Of the children who reached a low HRpeak, 42% showed a higher $\dot{V}O_2$supramaximal value. Of the children who had a low RERpeak, only 25% still improved during supramaximal testing. Despite the fact that fewer children with community ambulation reached an RERpeak of greater than 1.00 or a $\dot{V}O_2$ plateau, this difference did not result in significant differences in $\dot{V}O_2$peak and $\dot{V}O_2$supramaximal values between the groups. Of the 7 children who did not reach a $\dot{V}O_2$ plateau, only one still improved during the added step. Furthermore, 3 children who still improved had community ambulation, and 2 had normal ambulation. During the last minute of supramaximal testing, 4 of 5 children reached a $\dot{V}O_2$ plateau.

**Table 3.**
Exercise Testing of 20 Children With Spina Bifida

| Parameter[a] | $\bar{X}$ (SD) for Children: All | With Normal Ambulation | With Community Ambulation |
|---|---|---|---|
| $\dot{V}O_2$peak (L/min) | 1.23 (0.6) | 1.43 (0.6) | 1.02 (0.5) |
| $\dot{V}O_2$peak/kg (mL/kg/min) | 34.1 (8.3) | 39.4 (5.7) | 28.7 (7.0)[b] |
| HRpeak (bpm) | 183.8 (19.9) | 184.7 (20.4) | 182.3 (20.3) |
| RERpeak ($\dot{V}CO_2/\dot{V}O_2$) | 1.07 (0.1) | 1.09 (0.1) | 1.05 (0.1) |
| Peak ventilation (L/min) | 45.1 (22.2) | 51.4 (20.9) | 38.9 (22.6) |
| Peak $\dot{V}CO_2$ (L/min) | 1.34 (0.71) | 1.57 (0.7) | 1.11 (0.7) |
| Duration of testing (min) | 9.0 (4.0) | 10.4 (2.9) | 9.3 (5.0) |

[a] $\dot{V}O_2$peak=peak oxygen uptake, HRpeak=peak heart rate, RERpeak=peak respiratory exchange ratio, $\dot{V}CO_2$=carbon dioxide exhaled.
[b] $P<.05$ for difference between children with normal ambulation and children with community ambulation.

## Discussion

The purpose of the present study was to determine whether $\dot{V}O_2$peak measured during a graded treadmill exercise test reflects $\dot{V}O_2$max in children who have spina bifida and are ambulatory.

## Rowland Criteria

In the present study, the percentage of children meeting one of the Rowland criteria[39] was much higher than that in our earlier data. Seventy-five percent of the children in the present study met at least 2 of the 3 criteria, and only one child failed to meet any criteria. These findings are much more in line with the findings of earlier research with children who were healthy, which showed that $\dot{V}O_2$peak in children is a valid indicator of $\dot{V}O_2$max.[26] Gulmans et al[26] tested 158 children who were healthy and 12 to 18 years of age; 100% met the criteria for maximum

**Table 4.**
Rowland Criteria During Exercise Testing

| Parameter[a] | No. (%) of Children: All | With Normal Ambulation | With Community Ambulation |
|---|---|---|---|
| Signs of subjective criteria | 20 (100) | 10 (100) | 10 (100) |
| HRpeak of >95% (210 − age) | 13 (65) | 7 (70) | 6 (60) |
| RERpeak of >1.00 | 16 (80) | 9 (90) | 7 (70) |
| $\dot{V}O_2$ plateau | 13 (65) | 7 (70) | 6 (60) |

[a] HRpeak=peak heart rate (bpm), RERpeak=peak respiratory exchange ratio, $\dot{V}O_2$=oxygen uptake.

**Table 5.**
Individual Differences in Normalized Peak Oxygen Uptake ($\dot{V}O_2$peak) and Supramaximal Oxygen Uptake ($\dot{V}O_2$supramaximal) and Rowland Criteria[a]

| Subject No. | Ambulation Status | ($\dot{V}O_2$supramaximal/kg) − ($\dot{V}O_2$peak/kg) (mL/kg/min) | HRpeak (bpm) | RERpeak | $\dot{V}O_2$peak–$\dot{V}O_2$ in Last Minute (mL/kg/min) | No. of Rowland Criteria Met (of 3) |
|---|---|---|---|---|---|---|
| 1 | CA | −0.49 | 143[b] | 0.97[b] | 3.11[b] | 0 |
| 2 | NA | −2.92 | 201 | 1.18 | 1.02 | 3 |
| 3 | NA | 8.21[c] | 159[d] | 1.17 | 5.62[d] | 1 |
| 4 | CA | 3.09[c] | 189 | 0.92[d] | 1.98 | 2 |
| 5 | NA | 1.79 | 177[d] | 1.04 | 1.55 | 2 |
| 6 | NA | 0.04 | 192 | 1.03 | 0.61 | 3 |
| 7 | NA | 2.27[c] | 140[d] | 1.02 | 1.82 | 1 |
| 8 | CA | 3.65[c] | 200 | 1.06 | 1.61 | 3 |
| 9 | NA | −0.18 | 202 | 1.05 | 0.38 | 3 |
| 10 | CA | −0.18 | 188[d] | 1.19 | 1.1 | 2 |
| 11 | NA | −1.86 | 195 | 1.14 | 2.29[d] | 2 |
| 12 | CA | 0.85 | 210 | 1.29 | −0.32 | 3 |
| 13 | CA | −3.28 | 192 | 1.00 | 2.28[d] | 2 |
| 14 | CA | −1.46 | 191 | 1.27 | 1.54 | 3 |
| 15 | CA | 1.32 | 159[d] | 1.00 | 3.68[d] | 1 |
| 16 | CA | 4.88[c] | 165[d] | 1.02 | 0.55 | 2 |
| 17 | CA | −1.06 | 185 | 0.84[d] | 4.99[d] | 1 |
| 18 | NA | 1.79 | 198 | 1.30 | 2.35[d] | 2 |
| 19 | NA | −1.30 | 195 | 0.92[d] | 1.32 | 2 |
| 20 | NA | −1.11 | 188 | 1.06 | 0.27 | 3 |

[a] HRpeak=peak heart rate, RERpeak=peak respiratory exchange ratio, CA=community ambulation, NA=normal ambulation.
[b] Did not reach HRpeak of >95% (210 − age), RERpeak of >1.00, and $\dot{V}O_2$plateau.
[c] Increased by more than 2.1 mL/kg/min in the supramaximal test.
[d] Did not reach HRpeak of >95% (210 − age), RERpeak of >1.00, or $\dot{V}O_2$plateau.

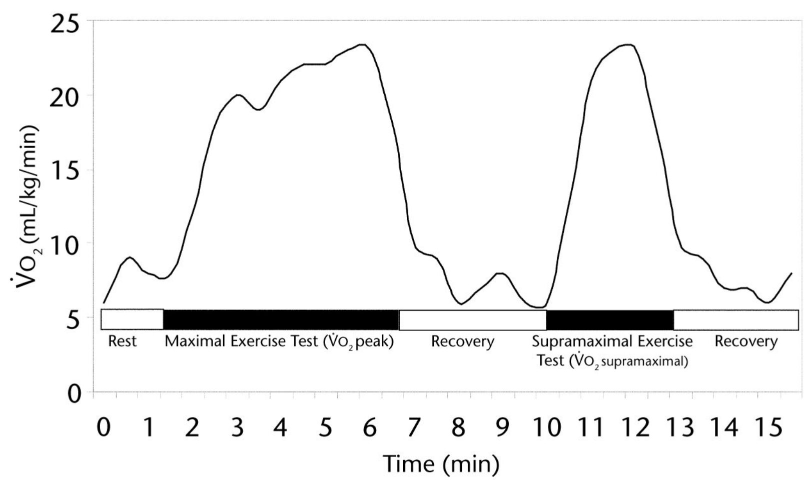


**Figure.**
Example of peak oxygen uptake ($\dot{V}O_2$peak) and supramaximal oxygen uptake ($\dot{V}O_2$supramaximal) testing.

exercise testing. The criteria used in that study were different from those used in the present study and included invasive testing but were still based on the guidelines described by Rowland.[1]

In a Danish study with a large sample of subjects,[28] 84% of the subjects met at least 2 of the 3 objective criteria described by Rowland,[39] a finding similar to that in the present study. The presence of a plateau in pediatric exercise testing has been disputed in the literature. Even though reaching a plateau often is considered to be the true criterion for maximum exercise testing, a literature review revealed that 21% to

95% of children, with an average of 55% of children who were healthy, reached a plateau during exercise testing.[13] In the present study, 70% of children reached a plateau; interestingly, however, reaching a plateau was not predictive of improvement during supramaximal testing. Four of 5 children reaching a higher $\dot{V}O_2$supramaximal value met the criteria for a $\dot{V}O_2$ plateau during initial testing, but only one of 7 children who did not reach a $\dot{V}O_2$ plateau improved during the added step.

### Supramaximal Protocol

Besides the Rowland criteria,[39] we used a protocol described by Rossiter et al[16] to determine whether the true $\dot{V}O_2$max had been reached during the graded treadmill exercise test. We did this by adding an extra step of testing at 110% of the maximum achieved speed. We found no significant differences between $\dot{V}O_2$peak and $\dot{V}O_2$supramaximal in children with either normal ambulation or community ambulation. These results are in line with those of other studies in which supramaximal protocols were used. Rowland[15] was unable to elicit an increase in $\dot{V}O_2$ during supramaximal testing in 9 children who were healthy. Rossiter et al[16] concluded that when subjects seem to give their maximal effort (Rowland subjective criteria), $\dot{V}O_2$peak most likely reflects $\dot{V}O_2$max. At the individual level, though, 5 children still continued to improve during supramaximal testing in the present study. Eighty percent of children reached a plateau during supramaximal testing, implying a maximal measurement of $\dot{V}O_2$ during the added step. Besides meeting fewer than 2 of the 3 criteria, a low HRpeak, in particular, seems to be an indication that an individual may not have reached the true $\dot{V}O_2$max.

The present study differed from our earlier studies in 2 ways.[23,24] First, the population tested in the present study included more subjects with community ambulation and children with a lesion at a higher level (and therefore more muscular deficits). Despite these differences, the HRpeak and RERpeak reached in the present study were higher than those achieved in our previous studies—but without reaching a higher $\dot{V}O_2$peak value. A secondary analysis revealed no correlation between HRpeak and the level of the lesion, in contrast to the results of a study by Agre et al.[11] This difference could be explained partly by the fact that children with a lesion at a higher level performed the treadmill test in a wheelchair; this mode of exercise was less strenuous than walking. In addition, a discontinuous and less-progressive testing protocol was used. Still, compared with the results of studies involving children who were healthy, HRpeak was much lower in our population (183.8 versus 196–199[28] or 199–200[41]). This finding likely was attributable to the fact that $\dot{V}O_2$peak in children who are ambulatory is determined not by cardiac limitations but rather by deconditioning, muscular deficiencies, or both, and possible ventilatory limitations.[23]

Second, we defined "ambulatory ability" in a different way in the present study; the decision about which treadmill protocol to use was based on actual performance during the 6MWT instead of functional classification. This change in protocol improved peak outcomes for our population.

### Limitations of the Study

In the context of the USAGE study, only children with spina bifida and community or normal ambulation were included. In future studies, it would be interesting to develop exercise testing for children who are considered to have "household ambulation" (Appendix 1) as well. Questions could be raised about a possible practice effect and familiarization with the test procedures for both the treadmill test and the 6MWT. At present, we are examining the reproducibility of exercise testing in children who have spina bifida and are ambulatory. A question could be raised about the frequent use of medications in children with spina bifida. It is unclear how such medications might interfere with $\dot{V}O_2$, utilization and transport systems in the body, and central and peripheral fatigue. In the present study, we monitored medication use during exercise testing.

## Conclusion

A graded treadmill exercise test is an appropriate method for measuring $\dot{V}O_2$peak in children with spina bifida and normal or community ambulation. For the selection of a treadmill protocol, it is important to use actual performance and not functional classification as a decisive factor. Levels of HRpeak (not RERpeak) that are lower than predicted may be an indication of submaximal effort. When the true character of maximum exercise testing of children who have spina bifida and are ambulatory is in doubt, a supramaximal step of testing at 110% of the maximum achieved speed is an easy and well-tolerated method for the confirmation and further interpretation of maximum exercise testing.

Mrs de Groot, Dr Takken, Dr Helders, and Dr Vanhees provided concept/idea/research design, writing, and fund procurement. Mrs de Groot, Dr Takken, and Ms de Graaff provided data collection. Mrs de Groot, Dr Takken, Ms de Graaff, and Dr Vanhees provided data analysis and project management. Dr Gooskens provided institutional liaisons. Mrs de Groot and Dr Gooskens provided participants. Dr Takken and Dr Helders provided facilities/equipment. Dr Takken, Ms de Graaff, Dr Gooskens, Dr Helders, and Dr Vanhees provided consultation (including review of manuscript before submission).

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## Appendix 1.
Adapted Hoffer Classification[6,7]

| Level of Ambulation | Description |
|---|---|
| Normal | Independent and unrestricted ambulation without use of assistive devices |
| Community | Independent outdoor ambulation with or without use of braces or assistive devices; use of wheelchair for longer distances |
| Household | Use of braces or assistive devices for indoor ambulation; use of wheelchair for outdoor locomotion |
| Nonfunctional | Walking only in therapeutic situations |
| None | Wheelchair dependent |

## Appendix 2.
Terminology[a]

| Term | Explanation |
|---|---|
| $\dot{V}O_2$ | Oxygen uptake (L/min); determined from cardiac output (heart rate × stroke volume) and arterial–mixed-venous oxygen content differences (=Fick formula) |
| $\dot{V}O_2$peak | Highest level of oxygen uptake ($\dot{V}O_2$) attained during a single test without necessity of flattening of the $\dot{V}O_2$ curve |
| $\dot{V}O_2$max | Maximum possible attainable level of oxygen utilization by both cardiorespiratory and neuromuscular systems, characterized by flattening of the $\dot{V}O_2$ curve despite an increase in workload; often determined in more than one test session; in people who are healthy, $\dot{V}O_2$peak and $\dot{V}O_2$max are interchangeable |
| $\dot{V}CO_2$ | Carbon dioxide exhaled (L/min) |
| RER | Respiratory exchange ratio; calculated as $\dot{V}CO_2/\dot{V}O_2$ |
| $\dot{V}E$ | Minute ventilation (L/min) |
| HR | Heart rate (bpm) |

[a] Based on: Wasserman K, et al. *Principles of Exercise Testing and Interpretation.* 4th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2005.