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REVIEW ARTICLE

Clinimetric Properties of the Steep Ramp Test to Assess Cardiorespiratory Fitness, Its Underlying Physiological Responses, and Its Current Applications: A Scoping Review

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Abstract

Objective: Providing an overview of the clinimetric properties of the steep ramp test (SRT)—a short-term maximal exercise test—to assess cardiorespiratory fitness (CRF), describing its underlying physiological responses, and summarizing its applications in current clinical and research practice.

Data Sources: MEDLINE (through PubMed), CINAHL Complete, Cochrane Library, EMBASE, and PsycINFO were searched for studies published up to July 2023, using keywords for SRT and CRF.

Study Selection: Eligible studies involved the SRT as research subject or measurement instrument and were available as full text articles in English or Dutch.

Data Extraction: Two independent assessors performed data extraction. Data addressing clinimetric properties, physiological responses, and applications of the SRT were tabulated.

Data Synthesis: In total, 370 studies were found, of which 39 were included in this study. In several healthy and patient populations, correlation coefficients between the work rate at peak exercise (WR_{peak}) attained at the SRT and oxygen uptake at peak exercise during cardiopulmonary exercise testing (CPET) ranged from .771-.958 (criterion validity). Repeated measurements showed intraclass correlation coefficients ranging from .908-.996 for WR_{peak} attained with the first and second SRT (test-retest reliability). Physiological parameters, like heart rate and minute ventilation at peak exercise, indicated that the SRT puts a lower burden on the cardiopulmonary system compared to CPET. The SRT is mostly used to assess CRF, among others as part of preoperative risk assessment, and to personalize interval training intensity.

Conclusions: The SRT is a practical short-term maximal exercise test that is valid for CRF assessment and to monitor changes in CRF over time in various healthy and patient populations. Its clinimetric properties and potential applications make the SRT of interest for a widespread implementation of CRF assessment in clinical and research practice and for personalizing training intensity and monitoring longitudinal changes in CRF.

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Cardiorespiratory fitness (CRF) refers to the capacity of the circulatory and pulmonary systems to extract oxygen from the air and transport it to skeletal muscles' mitochondria for energy production to enable physical activity.[1,2] CRF is strongly associated with mortality and morbidity in the general population. A recent meta-analysis by Han et al[3] showed an inverse association of CRF with all-cause, cardiovascular disease, and cancer mortality. Furthermore, a large body of epidemiologic and clinical research demonstrated that CRF is a potentially stronger and independent predictor of mortality than other established risk factors such as smoking, hypertension, high cholesterol, and type 2 diabetes.[1] In addition, a certain level of CRF is required for many activities of daily life—for instance, labor, active transport, household activities, and sports. Low levels of CRF can limit activity and participation in society.[4] As such, CRF is an important predictor of health outcomes,[1] closely related to functional independence and quality of life.[5]

Despite its well-established clinical importance, CRF assessment is scarcely implemented in current clinical practice for 2 major reasons.[1,6,7] First, there is still insufficient awareness among health care professionals of the importance of CRF, regarding not only health outcomes but also daily physical functioning and societal participation.[1] Second, cardiopulmonary exercise testing (CPET), which is the criterion standard to assess CRF,[8] is often not feasible or is considered too costly and time consuming in clinical practice.[9] CPET requires advanced equipment for respiratory gas analysis and heart rate monitoring and specialized knowledge to adequately perform the procedures and interpret test results. Moreover, the use of a face mask while performing a maximal effort can be perceived as burdensome, especially for patients. To facilitate a widespread implementation of CRF assessment in clinical practice, a more practical yet accurate alternative exercise test that is applicable to participants with CRF levels from very low to very high is urgently needed.

The steep ramp test (SRT) is a practical test that could be used as an alternative to CPET for CRF assessment in clinical practice. The SRT is a short-term maximal exercise test on a cycle ergometer introduced by Meyer et al[10] in their study on rehabilitation of adult patients with chronic heart failure. They developed the SRT to personalize training intensity for the high-intensity phases of an interval training program on a cycle ergometer. The original SRT protocol starts with a warm-up phase of 3 minutes of unloaded cycling, after which the work rate starts to increase rapidly (25W every 10s until the patient can no longer maintain the pedaling frequency ≥60rpm).[10] The SRT test procedure is relatively short (approximately 15min in total, with a work rate increment phase of 2-4min) compared to CPET (approximately 45min in total, with a work rate increment phase of 8-12min). The primary outcome measure of the SRT is the achieved work rate at peak exercise (WR_{peak}), which is assumed to be a predictor of CRF without requiring respiratory gas analysis measurements.[11] The SRT has been recommended in several clinical guidelines,[12-14] as well as by several research groups,[9,15,16] as a short and practical alternative for CPET to assess CRF. Despite its potential usefulness, the SRT is not widely applied in clinical practice yet, possibly because health care professionals are not aware it exists or because its clinimetric properties and utility are not well-known. Therefore, the objective of this scoping review was to provide an overview of the clinimetric properties of the SRT to assess CRF, describe the physiological responses to the SRT, and identify the different applications of the SRT in current clinical and research practice.

List of abbreviations:

6MWT	**6-minute walk test**
COPD	**chronic obstructive pulmonary disease**
CPET	**cardiopulmonary exercise testing**
CRF	**cardiorespiratory fitness**
HR_{peak}	**heart rate at peak exercise**
ICC	**intraclass correlation coefficient**
iSWT	**incremental shuttle walk test**
MCID	**minimal clinically important difference**
PRISMA-ScR	**Preferred Items for Systematic Reviews and Meta-Analysis Extension for Scoping Reviews**
RER	**respiratory exchange ratio**
RER_{peak}	**respiratory exchange ratio at peak exercise**
RPE	**rate of perceived exertion**
SRT	**steep ramp test**
VE_{peak}	**minute ventilation at peak exercise**
VO_{2peak}	**oxygen uptake at peak exercise**
WR_{peak}	**work rate at peak exercise**

Methods

Study design

This scoping review was conducted according to the 5-stage scoping review process suggested by Arksey and O'Malley[17] and refined by Levac et al.[18] Furthermore, this study was conducted and reported according to the Preferred Items for Systematic Reviews and Meta-Analysis Extension for Scoping Reviews (PRISMA-ScR) guidelines.[19]

Search strategy and study selection

To identify relevant studies, an extensive search strategy (appendix A) was developed in cooperation with an experienced research librarian of the Martini Hospital, Groningen, The Netherlands. The primary search terms included "steep ramp test," "steep ramp anaerobic test," "SRT," "SRAT," "cardiorespiratory fitness," "physical fitness," "exercise test," and "exercise tolerance." An exploratory search was conducted in the PubMed and Cochrane Library databases. Keywords identified in the titles and abstracts of obtained studies were used to adjust the search string. Subsequently, the electronic databases of MEDLINE (through PubMed), CINAHL Complete, Cochrane Library, EMBASE, and PsychINFO were searched up to July 18, 2023.

Studies were considered eligible if they used the SRT as measurement instrument or as research object, were available as a full text article in English or Dutch, and were published in a peer-reviewed journal. Results from all database searches and hand searching the literature were combined, and duplicates were removed with the help of the tool Rayyan.[20,a] To ensure a clean reviewing process, 2 assessors (IT-K and EK) independently screened all titles and abstracts to determine eligibility. To ensure that at least 75% agreement was reached between the assessors in determining eligibility based on study titles and abstracts, a pilot was performed using 25% (n=65) of the references. This pilot did not result in adjustments in the inclusion criteria or keywords, because agreement was found in 99.4% of the screened references. After the pilot evaluation, both assessors analyzed the titles and abstracts of the remaining 75% of the studies. Finally, the reference lists of all studies identified were hand searched for any additional studies. Disagreements regarding inclusion or exclusion were resolved by mutual discussion; when necessary, a third independent assessor (MA) was consulted.

Data extraction

Results from included studies were extracted and tabulated descriptively under 3 main categories: (1) clinimetric properties (ie, validity, reliability, responsiveness, specific aspects to consider for measurement error), (2) physiological responses to the SRT, and (3) applications in clinical and research practice (ie, personalized work rate calculation for a physical exercise training program, assessment of CRF) of the SRT. General information (author and year), methodological data (population and sample size), and other relevant information were extracted and presented.

Quality assessment

For studies on the clinimetric properties of the SRT (ie, validity to assess CRF, test-retest reliability, and/or responsiveness to a change in CRF), methodological quality was evaluated independently by the 2 assessors using the COSMIN Risk of Bias checklist for PROMs[21] and the COSMIN Risk of Bias tool to assess the quality of studies on reliability or measurement error of outcome measurement instruments.[22] In case of disagreement, the third independent assessor was consulted.

Results

In total, 367 eligible studies were identified from the databases. Three studies were added through hand searching. Based on title and abstract screening, 110 duplicates were removed and an additional 195 articles were excluded, as these did not match the inclusion criteria. Eight additional studies were identified through reference scanning. Thus, 73 full text articles were assessed for eligibility. Based on full text assessment, 34 studies were excluded for a diversity of reasons. For 2 of these 34 studies, assessors disagreed about eligibility, and 7 studies were labeled as ‘maybe included’ by both assessors. Consensus was reached by discussion for all these studies. Finally, a total of 39 studies were included in this scoping review, as shown in the PRISMA-ScR flowchart depicted in fig 1.

Terminology

Different terms were used in the included studies to indicate the primary outcome measure of the SRT. “Peak work rate” (W_{peak} or WR_{peak}) or “maximal work rate” (W_{max} or WR_{max}) were used most frequently, but also “(peak) power output,” “maximal short exercise capacity,” “short time muscular exercise capacity,” and “steep ramp test work rate” were used. To optimize readability, the term WR_{peak} is used consistently throughout this manuscript.

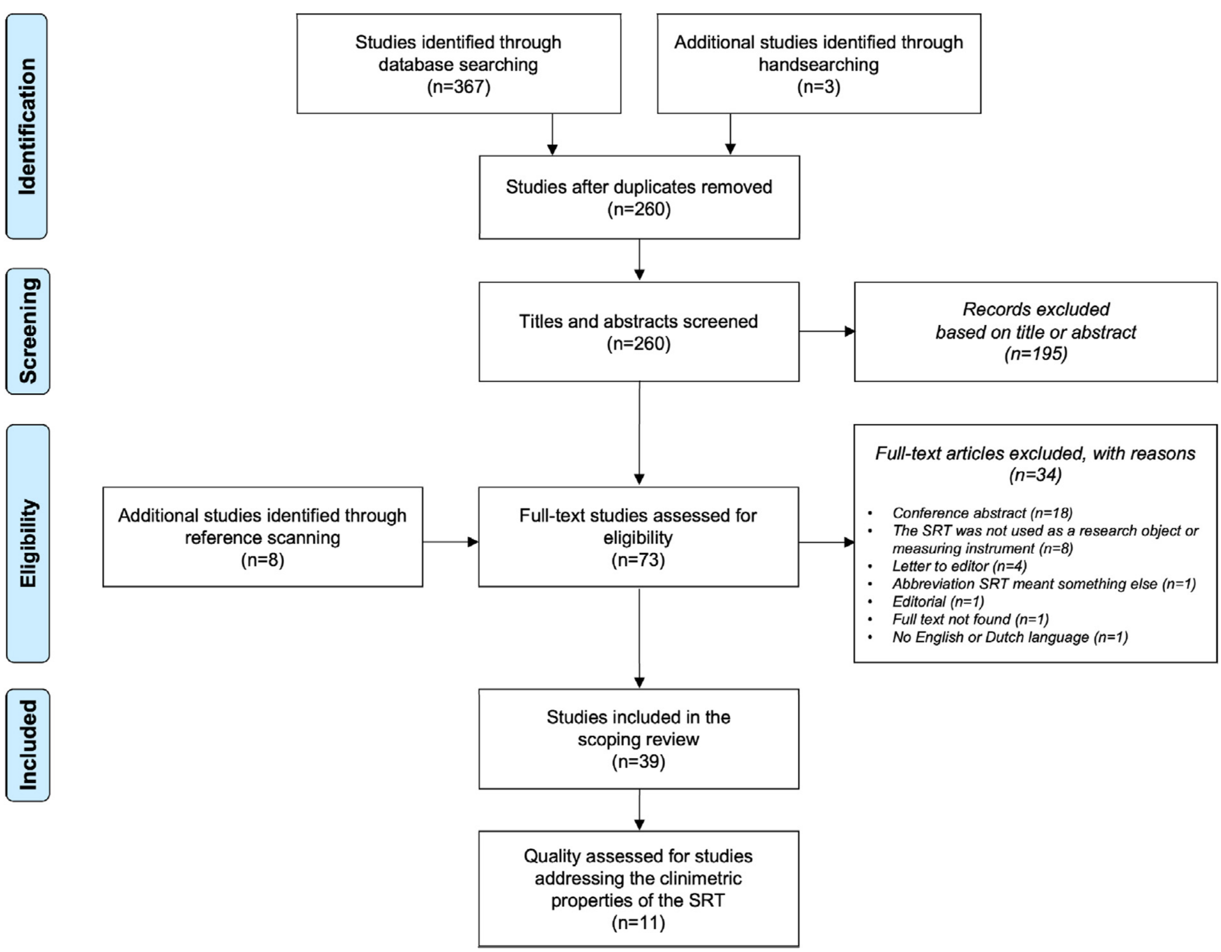

Fig 1 PRISMA-ScR flowchart for the study selection process.

Steep ramp test protocols used

In the literature, several modifications to the original SRT protocol were used (fig 2). According to the original protocol, the test starts with a 3-minute warm-up of unloaded cycling, where after thework rate increases in steps of 25 Watts every 10 seconds.[10] In 22 studies[10,13,15,23-41] (56.4%) this stepwise protocol was used, while in the other 17 studies[9,11,16,42-55] (43.6%), a linear ramp protocol was used to increase work rate. Variation was also found in the steepness of the ramp (work rate increments). In 27 studies[10,13,15,16,23,25-40,42,44-46,49,50] (69.2%), work rate increased according to the original protocol.[10] In 7 studies[9,11,24,43,53-55] (18.0%), work rate increments were lowered to make the SRT feasible for children and adolescents (increments of 10, 15, or 20W each 10s in a ramp-like manner for children <120cm, 120-150cm, and >150cm, respectively). In 5 studies[41,47,48,51,52] (12.8%), work rate increments were lowered to make the SRT feasible for unfit (elderly) surgical patients (increments of 10W every 10s in a ramp-like manner). Finally, the description of SRT termination criteria varied between studies. In 37 (94.9%) of the included studies, peak exercise was defined as the point at which the patient's pedaling rate dropped below 60[9-11,13,15,16,24,25,27-31,35,37-55] or 50[23,32,33,36] rpm. In 2 studies (5.1%), peak exercise was defined as volitional fatigue[26] and exhaustion.[34]

Interpretation of steep ramp test results

Age- and sex-related norm values for SRT WR_{peak} are available for children and adolescents[43] (n=252, age 8-19y) based on the body height−dependent ramp protocol. More recently, these norm values were extended with WR_{peak} values for young adults (n=57, age 19-25y), attained with a ramp version of the original SRT protocol.[46] For adults aged ≥25 years, norm values for SRT performance are currently not available. Instead, to facilitate SRT interpretation, prediction equations were developed to predict oxygen uptake at peak exercise ($\dot{V}O_{2peak}$) from SRT WR_{peak}.[11,13,25] In a small sample of adult cancer survivors (n=37), the following prediction equation was developed: $\dot{V}O_{2peak}$ (mL/min)=(6.7 × SRT WR_{peak} [W]) + 356.7, (R^2 .672, SEE 616 mL/min).[25] Ten years later, body mass and sex were added to this prediction equation, based on a larger population of adult cancer survivors (n=283).[13] This adjustment led to the following equation: $\dot{V}O_{2peak}$ (mL/min)=(3.92 × SRT WR_{peak} [W]) + (5.02 × body mass [kg])−(327.6 × sex [female: 1; male: 0] + 676.8), and resulted in an increase in the intraclass correlation coefficient (ICC) between measured $\dot{V}O_{2peak}$ and predicted $\dot{V}O_{2peak}$ (from .61-.73) and a decrease in measurement error (from ±705 mL/min to ±608 mL/min).[13] Before pediatric norm values became available for SRT performance, the following prediction equation was developed in a small sample of children and adolescents (n=37): $\dot{V}O_{2peak}$ (mL/min)=(8.262 × SRT WR_{peak} [W]) + 177.096 (R^2 .917, SEE 237.4 mL/min).[11]

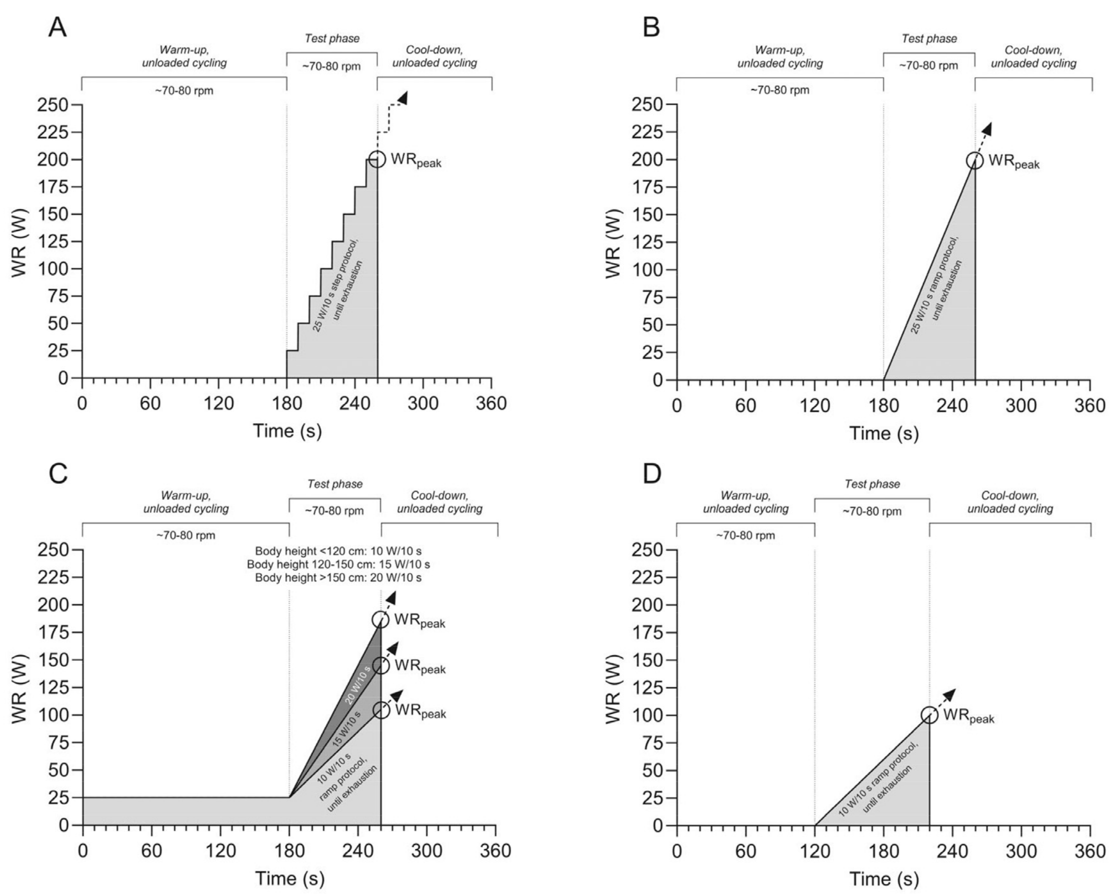

Fig 2 **(A)** The original SRT protocol. Three modifications to the original protocol: **(B)** a "true" SRT ramp protocol, **(C)** a body height−dependent pediatric SRT protocol, and **(D)** an SRT protocol for (unfit) elderly.

Clinimetric properties of the steep ramp test

Clinimetric properties of the SRT were assessed in 11 studies, in a total of 581 participants (table 1). Included studies evaluated the validity to assess CRF (n=8),[9,11,23-26,42,45] test-retest reliability (n=4),[11,15,25,42] responsiveness to a change in CRF (n=2),[16,45] and the minimal clinically important difference (MCID)[40] of the SRT (n=1).

Validity to assess cardiorespiratory fitness

In 6 studies,[9,11,23,25,42,45] the criterion validity of the SRT to estimate CRF was determined by examining the relationship between the SRT WR_{peak} and CPET Vo_{2peak} (table 1). These studies included adults with cancer and cancer survivors (n=143),[25,45] adults with type 2 diabetes (n=61),[42] children with cancer and pediatric cancer survivors (n=61),[23] children with cystic fibrosis (n=40),[9] and healthy children and adolescents (n=38).[11] The correlation between SRT WR_{peak} and CPET Vo_{2peak} was strong in all studies (r values ranging from .771-.958). The methodological quality of the abovementioned studies was considered "very good" in 5 studies and "doubtful" in 1 study (online supplementary file 1, table 1). The quality of this evidence was considered high.

In 3 studies,[24,26,42] the construct validity of the SRT was determined (table 1). In adults with type 2 diabetes (n=61),[42] a strong correlation was found between SRT WR_{peak} and CPET WR_{peak} (r .90 in both females and males). In a small sample of adults with moderate-to-severe chronic obstructive pulmonary disease (COPD) (n=13),[26] a moderate correlation was found between the SRT WR_{peak} normalized for body mass and CPET WR_{peak} normalized for body mass (r .573). In a small sample of adolescents with cystic fibrosis (n=16),[24] the SRT was performed with respiratory gas analysis measurements, and SRT Vo_{2peak} was compared to CPET Vo_{2peak}. A strong correlation was found between Vo_{2peak} values derived from both tests (r .98). The methodological quality of the abovementioned studies was considered "very good" in 2 studies and "doubtful" in 1 study (online supplementary file 1, table 1). The quality of this evidence was considered moderate.

Test-retest reliability

In 4 studies, the test-retest reliability of the SRT was investigated. These studies included healthy children and adolescents (n=37),[11] adults with moderate-to-severe COPD (n=11),[15] adult cancer survivors (n=23),[25] and adults with type 2 diabetes (n=40).[42] All studies reported very high ICCs (ranging from .908-.996) for WR_{peak} values derived from the first and the second SRT (table 1). The methodological quality of the abovementioned studies was "very good" in 1 study, "adequate" in 2 studies, and "doubtful" in 1 study (online supplementary file 1, table 2). The quality of this evidence was considered high.

Responsiveness to a change in cardiorespiratory fitness

In 2 studies,[16,45] the responsiveness or longitudinal validity of the SRT to change in CRF was investigated. In adult women with breast cancer (n=161) who were monitored over time to see whether changes in CRF assessed by CPET were also indicated by SRT performance, a significant moderate correlation was found between CPET Vo_{2peak} and SRT WR_{peak} over time (β 0.61; 95% confidence intervals [CI], .51-.70).[16] In adult cancer survivors (n=59) who participated in a 10-week physical exercise rehabilitation program, the change in SRT WR_{peak} was compared with the change in CPET Vo_{2peak}.[45] After the training program, CPET Vo_{2peak} increased on average by 2.0±2.3 mL/kg/min, whereas SRT WR_{peak} increased on average by 0.4±0.3 W/kg. A moderate correlation was found between the change in SRT WR_{peak} and CPET Vo_{2peak} (r .51). The methodological quality of both studies was considered "very good" (online supplementary file 1, table 2). The quality of this evidence was considered high.

Minimal clinically important difference

In 1 study,[40] the MCID, defined as the smallest change in SRT WR_{peak} that a patient would classify as important, was determined. In adults with chronic musculoskeletal pain (n=307), a difference of 25-55 W in SRT WR_{peak} scores was determined as MCID.

Physiological responses to the steep ramp test

In 7 studies, the physiological responses to the SRT were investigated (table 2). Three studies[11,15,23] focused on the physiological responses to the SRT as their primary aim, while the physiological responses were analyzed as a secondary aim in the other 4 studies.[9,24,27,42] Participants included healthy children and adolescents (n=38),[11] children with cancer during treatment or no longer than 1 year after treatment (n=61),[23] adolescents with cystic fibrosis (n=56),[9,24] adults with moderate-to-severe COPD (n=11),[15] adults with chronic congestive heart failure (n=18),[27] and adults with type 2 diabetes (n=61).[42] Results showed that Vo_{2peak} and Vo_{2peak} normalized for body mass were lower,[9,15,23,24,27,42] but not statistically significant in all studies (P>.05),[15,23,24] at the SRT compared to CPET. Heart rate at peak exercise (HR_{peak}) was also lower at the SRT compared to CPET; however, only in 4[9,11,23,42] of the 7 studies were these differences statistically significant (P<.05). With regard to minute ventilation at peak exercise (VE_{peak}), results varied between studies. Four studies[9,11,23,24] found lower values of VE_{peak} at the SRT compared to CPET. In 3 of these studies,[9,11,23] these differences were statistically significant (P<.05). In 1 study,[24] VE_{peak} was slightly higher at the SRT compared to CPET, but these differences were not statistically significant (P>.05). The respiratory exchange ratio at peak exercise (RER_{peak}) was significantly lower (P<.05) at the SRT compared to CPET in all but 1 study[9,23,24,27,42]; more specifically, 1 study[42] with male participants with type 2 diabetes reported no differences (P>.05) for RER_{peak}.

Besides these physiological parameters, 7 studies[9,11,15,23,24,27,42] examined the difference in WR_{peak} between SRT and CPET, and 3 studies[9,11,42] examined the difference in rate of perceived exertion (RPE). Results showed that WR_{peak}[9,11,15,23,24,27,42] and WR_{peak} normalized for body mass[11,23] attained with the SRT significantly exceeded CPET values (P<.05), which indicates that the SRT has a supramaximal nature. Results for RPE varied between studies. In 2 studies,[9,11] RPE scores at peak exercise were significantly lower with the SRT (P<.05), while in 1 study[42] no significant difference (P>.05) was found.

Steep ramp test applications

In 28 studies, the SRT was applied in clinical and research practice to assess CRF (n=14), to personalize training intensity for a physical exercise training program (n=11), or both (n=3) (table 3). In 7 studies in which the SRT was used for CRF assessment, SRT performance was part of the preoperative risk assessment.

Table 1 Clinimetric properties of the SRT

Authors (y)	Country	Number of Participants (Males) Study Population Mean Age (y±SD)	SRT Protocol: Warm-Up Duration and Intensity Work Rate Increments Stop Criterion	Comparison Correlation Coefficient	*P* Value	Important Conclusions	WR_{peak} T1 (W) WR_{peak} T2 (W) ICC	*P* Value	WR_{peak} T1 (W/kg) WR_{peak} T2 (W/kg)	*P* Value ICC
Validity to assess CRF										
Bongers et al[11] (2013)	The Netherlands	n=38 (17 males) Healthy children and adolescents 13.9±3.2 y	3 min at 25 W Body height-dependent: 10, 15, or 20 W/10 s (ramp like) (<120cm, 120-150cm, or >150cm, respectively) Pedaling rate <60 rpm	SRT WR_{peak} – CPET Vo_{2peak} *r* .958	<.001	The SRT seems to be a valid exercise test that can predict CPET Vo_{2peak} in healthy children and adolescents	NA	NA	NA	NA
Bongers et al[9] (2015)	The Netherlands	n=40 (17 males) Adolescents with mild-to-moderate cystic fibrosis M: 15.1±2.1 y F: 14.3±1.2 y	3 min at 25 W Body height–dependent: 10, 15, or 20 W/10 s (ramp like) (<120cm, 120-150cm, or >150cm, respectively) Pedaling rate <60 rpm	SRT WR_{peak} – CPET Vo_{2peak} *r* .822	<.001	SRT WR_{peak} is strongly correlated to CPET Vo_{2peak} in adolescents with mild-to-moderate cystic fibrosis	NA	NA	NA	NA
Braam et al[23] (2015)	The Netherlands	n=61 (33 males) Children with cancer 12.9±3.0 y	1 min rest 3 min at 0 W 25 W/10 s (stepwise) Pedaling rate <50 rpm	SRT WR_{peak} – CPET Vo_{2peak} *r* .883	<.001	The SRT seems to be a valid instrument to assess CRF in children with cancer	NA	NA	NA	NA
Butcher et al[26] (2012)	Canada	n=13 (8 males) Adults with moderate-to-severe COPD 74.1±3.5 y	2 min at 0 W 25 W/10 s (stepwise) Volitional fatigue	SRT WR_{peak} – CPET WR_{peak} *r* .573	>.05	NR	NA	NA	NA	NA
De Backer et al[25] (2007)	The Netherlands	n=37 (10 males) Adult cancer survivors treated with chemotherapy 48±11 y	30 s at 25 W 25 W/10 s (stepwise) Pedaling rate <60 rpm	SRT WR_{peak} – CPET Vo_{2peak} (wk 0) *r* .82 (95% CI, .67-.90) SRT WR_{peak} – CPET Vo_{2peak} (wk 18) *r* .85 (95% CI, .72-.92)	.01 <.01	The SRT seems to be practical, reliable, and valid for the assessment of training dose A model was developed with only SRT (WR_{peak}) to predict CRF	NA	NA	NA	NA
Rozenberg et al[42] (2015)	The Netherlands	n=61 (35 males) Adults with type 2 diabetes M: 54.5±11.1 y F: 60.4±10.5 y	4 min rest 2 min at 0 W 25 W/10 s (ramp like) Pedaling rate <60 rpm	SRT WR_{peak} – CPET WR_{peak} (ramp) M: *r* .904 (95% CI, .817-.950) F: *r* .902 (95% CI, .792-.955)	<.05 (males) <.05 (females)	The SRT provides a feasible and valid alternative to determine CRF in untrained patients with type 2 diabetes	NA	NA	NA	NA
Weemaes et al[45] (2021)	The Netherlands	n=106 (28 males) Adult cancer survivors 56.6±11.0 y	3 min at 25 W 25 W/10 s (ramp like) Pedaling rate <60 rpm	SRT WR_{peak} – CPET Vo_{2peak} *r* .86 (95% CI, .80-.90)	NR	The SRT is a valid tool to estimate CRF in cancer survivors	NA	NA	NA	NA
Werkman et al[24] (2011)	The Netherlands	n=16 (8 males) Adolescents with cystic fibrosis 14.6±1.7 y	1 min rest 1 min at 0 W Body height– dependent: 10, 15, or 20 W/10 s (stepwise) based on body height (<120cm, 120-150cm, or >150cm, respectively) Pedaling rate <60 rpm	SRT WR_{peak} – CPET WR_{peak} *r* .91 SRT Vo_{2peak} – CPET Vo_{2peak} *r* .98	<.001 <.01	The SRT confirmed that CPET seems to be appropriate to assess Vo_{2peak} in adolescents with cystic fibrosis	NA	NA	NA	NA
Test-retest reliability										
Bongers et al[11] (2013)	The Netherlands	n=37 (17 males) Healthy children and adolescents 13.9±3.2 y	3 min at 25 W Body height–dependent: 10, 15, or 20 W/10 s (ramp) based on body height (<120 cm, 120-150 cm, or >150 cm, respectively) Pedaling rate <60 rpm	NA	NA	The SRT seems to be a reliable exercise test in healthy children and adolescents	T1: 277±93 W T2: 284±97 W ICC .986 (95% CI, .973-.993)	*P*<.001	T1: 5.2±0.8 W/kg T2: 5.3±0.9 W/kg ICC .935 (95% CI, .878-.966)	*P*<.001
Chura et al[15] (2012)	Canada	n=11 (7 males) Adults with moderate-to-severe COPD 71±3 y	2 min at 0 W 25 W/10 s (stepwise) Pedaling rate <60 rpm	NA	NA	The SRT is a highly reliable and feasible test in patients with COPD and may be useful in estimating leg muscle power	T1: NR T2: NR ICC .99	CV=3.8%	T1: NR T2: NR	NR

(*continued on next page*)

Table 1 (*Continued*)

Authors (y)	Country	Number of Participants (Males) Study Population Mean Age (y±SD)	SRT Protocol: Warm-Up Duration and Intensity Work Rate Increments Stop Criterion	Comparison Correlation Coefficient	*P* Value	Important Conclusions	WR_{peak} T1 (W) WR_{peak} T2 (W) ICC	*P* Value	WR_{peak} T1 (W/kg) WR_{peak} T2 (W/kg)	*P* Value ICC
De Backer[25] (2007)	The Netherlands	n=23 (not reported; for the whole group n=37, 10 males) Adult cancer survivors treated with chemotherapy Not reported; mean age of the whole group was 48±11 y	30 s at 25 W 25 W/10 s (stepwise) Pedaling rate <60 rpm	NA	NA	The test-retest reliability of the SRT was very high in adult cancer survivors treated with chemotherapy	T1: NR for subgroup, but for total group: 270±75 W T2: NR for subgroup, but for total group: 307±73 W ICC .996 (95% CI, .989-.998)	*P*<.01	T1: NR for subgroup, but for total group: 3.50±0.90 W/kg T2: NR for subgroup, but for total group: 4.01±0.88 W/kg ICC NR	NR
Rozenberg et al[42] (2015)	The Netherlands	n=40 (29 males) Adults with type 2 diabetes M: 54.5±11.1 y F: 60.4±10.5 y	4 min rest 2 min at 0 W 25 W/10 s (ramp like) Pedaling rate <60 rpm	NA	NA	The SRT has a high test-retest reliability in untrained patients with type 2 diabetes	T1: M: 316±81 W F: 177±67 W T2: M: 319±84 W F: 178±59 W M: ICC .951 (95% CI, .899-.977) F: ICC .908 (95% CI, .727-.971)	*P*<.05 (M) *P*<.05 (F)	NR	NR
Responsiveness to a change in CRF										
Van de Wiel et al[16] (2022)	The Netherlands	n=161 (0 males) Adult women with breast cancer treated with chemotherapy Group 1 (at the start of chemotherapy): 45.9±9.8 y Group 2 (shortly after chemotherapy): 50.5±10.1 y Group 3 (12wk after chemotherapy): 51.7±9.9 y	3 min at 10 W 25 W/10 s (ramp like) Pedaling rate <60 rpm	SRT WR_{peak} − CPET $\dot{V}O_{2peak}$ at the start of chemotherapy, directly after chemotherapy, and 12 wk after chemotherapy *β* .61 (95% CI, .51-.70)	<.01	It is recommended to use the SRT WR_{peak} directly instead of estimating CPET $\dot{V}O_{2peak}$ from SRT performance for monitoring purposes	NA	NA	NA	NA
Weemaes et al[45] (2021)	The Netherlands	n=106 (28 males) Adult cancer survivors 56.6±11.0 y	3 min at 25 W 25 W/10 s (ramp like) Pedaling rate <60 rpm	Δ SRT WR_{peak} − Δ CPET $\dot{V}O_{2peak}$ after a 10-wk physical exercise training program *r* .51 (95% CI, .29-.68)	NR	Unless the responsiveness of the SRT to measure changes in CRF appears moderate, the SRT seems able to detect improvement in CRF	NA	NA	NA	NA
MCID										
Benaim et al[40] (2019)	Switzerland	n=307 (not reported) Adults with chronic musculoskeletal pain Unknown for the group with SRT scores; for total group: 44±11 y	30 s at 25 W 25 W/10 s (stepwise) Pedaling rate <60 rpm	NA	NA	MCID: 25-55 W	NA	NA	NA	NA

Abbreviations: F, females; M, males; NA, not applicable; NR, not reported.

Table 2 Physiological responses to the SRT

Authors (y)	Country	Number of Participants Study Population Age (y)	WR_{peak} (W) (Mean ± SD) SRT vs CPET Difference *P* Value	WR_{peak} (W/kg) (Mean ± SD) SRT vs CPET Difference *P* Value	Vo_{2peak} (L/min or mL/min) Mean ± SD) SRT vs CPET Difference *P* Value	Vo_{2peak} (mL/kg/min) Mean ± SD) SRT vs CPET Difference *P* Value	RER_{peak} (Mean ± SD) SRT vs CPET Difference *P* Value	HR_{peak} (Mean ± SD) SRT vs CPET Difference *P* Value	VE_{peak} (Mean ± SD) SRT vs CPET Difference *P* Value	RPE at Peak Exercise (Mean ± SD) SRT vs CPET Difference *P* Value
Bongers et al[11] (2013)	The Netherlands	37 (17 males) Healthy children and adolescents 13.9±3.2 y	290±94 vs 203±69 W +70% *P*<.001	5.7±0.7 vs 4.0±.6 W/kg +70.2% *P*<.001	NR	NR	NR	181±10 vs 193±9 beats/min +13.5% *P*<.001	80.7±30.2 vs 93.3± 30.7 L/min −13.5% *P*<.001	5.9±1.7 vs 7.2±1.8 −18.1% *P*<.001
Bongers et al[9] (2015)	The Netherlands	40 (17 males) Adolescents with cystic fibrosis M: 15.1±2.1 y F: 14.3±1.2 y	252±60 vs 174±46 W +44.8% *P*<.001	5.0±.8 vs 3.5±.6 W/kg +42.9% *P*<.001	NR	36.9±7.5 vs 41.5±7.6 mL/kg/min −11.1% *P*=.008	1.10±.15 vs 1.12±.11 −1.8% *P*=.600	168±14 vs 182±12 beats/min −7.7% *P*<.001	59.2±19.5 vs 72.0± 20.2 L/min −17.8% *P*=.006	OMNI at peak exercise 5.5±2.3 vs 6.7±2.2 −17.9% *P*=.043
Braam et al[23] (2015)	The Netherlands	61 (33 males) Children with cancer 12.9±3.0 y	200.0 (IQR: 150-270) vs 122.8 (IQR: 90-167) W +62.9% *P* value NR	NR	1.3 (IQR: 0.94-1.86) vs 1.4 (IQR: 1.18-1.97) L/min −7.1% *P* value NR	26.6 (IQR: 22.2-34.0) vs 29.8 (IQR: 24.2-36.4) mL/kg/min −10.7% *P* value n. NR	1.2 (IQR: 1.06-1.37) vs 1.2 (IQR: 1.13-1.25) 0% *P* value NR	173 (IQR: 165-185) vs 191 (IQR: 182-196) beats/min −9.4% *P* value NR	47.8 (31.4-66.4) vs 52.0 (43.5-77.8) L/min −8.1% Mean difference: 9.2 (95% CI, −42.1-54.3)	NR
Chura et al[15] (2012)	Canada	11 (7 males) Patients with moderate-to-severe COPD 71±3 y	156.8±67.9 vs 65.9±35.9 W +237.9% *r* .887 *P*<.05	NR	1.07±.41 vs 1.11±.46 L/min −3.6% *r* .891 *P*<.05	NR	0.90± .07 vs 1.00±.13 −10.0% *r* .549 *P*>.001	109.8±19.7 vs 111.9 ± 20.9 beats/min -1.9% *r* 0.684 *P*<.05	38.94±13.01 vs 40.45± 13.33 L/min −3.73% *P* value NR	Dyspnea at peak exercise: 5.5±2.1 vs 5.6±1.8 Leg fatigue at peak exercise: 5.6±1.8 vs 5.7±1.7 dyspnea: −1.8% leg fatigue: −1.8% *P* value NR
Meyer et al[27] (1997)	Germany	18 (18 males) Patients with chronic congestive heart failure 52±2 y	200±11 vs 79±4 W + 253.2% *P*<.001	NR	1089±60 vs 950±88 mL/min −12.8% *P*<.001	NR	1.06±.02 vs 0.90±.02 -4.6% *P* value NR	116±4 vs 112±4 beats/min −3.4% *P* value NR	NR	NR
Rozenberg et al[42] (2015) males	The Netherlands	61 (35 males) Patients with type 2 diabetes M: 54.5±11.1	307 84 vs 193±63 W +59.1% *P*<.001	NR	2306±714 vs 2503±749 mL/min −7.9% *P*=.02	NR	1.11±.15 vs 1.11±.08 −0.0% *P* value NR	135±19 vs 143±20 beats/min −5.6% *P*<.001	NR	Borg at peak exercise 17±1 vs 16±1 +6.3% *P* value NR
Rozenberg et al[42] (2015) females	The Netherlands	61 (35 males) Patients with type 2 diabetes F: 60.4±10.5 y	188±55 vs 106±33 W +77.4% *P*<.001	NR	1389±376 vs 1496±342 mL/min −7.2% *P*=.04	NR	0.95±.15 vs 1.08±.09 −13.7% *P*<.001	125±25 vs 138±28 beats/min +10.4% *P*<.001	NR	NR
Werkman et al[24] (2011)	The Netherlands	16 (8 males) Adolescents with cystic fibrosis 14.6±1.7 y	244.5±71.9 vs 163.0±45.4 W +50% *P*<.01	4.9± .8 vs 3.3±.5 W/kg +48.5% *P*=.35	1.9±.7 vs 1.9±.6 L/min 0% *P*=.81	38.8±8.5 vs 38.9±7.4 mL/kg/min −0.3% *P*=.81	1.0±.1 vs 1.2±.1 −16.6% *P*<.01	179.2±13.1 beats/min vs 177.2±11.9 beats/min +1.1% *P*=.35	70.6±31.6 vs 69.5± 25.2 L/min +1.6% *P*=.66	NR

Abbreviations: IQR, interquartile range; NR, not reported; OMNI, Children's OMNI Scale of Perceived Exertion.

Table 3 SRT applications

Authors (y)	Country	Number of Participants (Males) Study Population Age (y ± SD)	SRT Protocol Warm-Up Intensity and Duration Test Termination Criterion	Brief Description/Aim of the SRT
Application: Personalizing high-intensity interval training				
Anagnostakou et al[34] (2011)	Greece	28 (23 males) Adults with stable chronic heart failure 53±10 y	25 W/10 s (stepwise) NR Exhaustion	Training intensity for interval training was set at 50% of the WR_{peak} achieved at the baseline SRT All patients underwent an SRT every 6 wk to readjust training intensity
Freyssin et al[36] (2012)	France	12 (6 males) Adults with chronic heart failure 54 9 y	25 W/10 s (stepwise) 10-min warm-up at 5 W Pedaling rate <50 rpm and exhaustion	Training intensity was set at 50% and 80% of the baseline SRT WR_{peak} in the first and last 4 wk of the rehabilitation program, respectively
Kampshoff et al[35] (2015)	The Netherlands	277 (55 males) Adult cancer survivors 54±11.0 y (high-intensity exercise group) 53±11.3 y (low-to-moderate intensity exercise group)	25 W/10 s (stepwise) 30-s warm-up at 25 W Pedaling rate <60 rpm	Training intensity was defined by the achieved SRT WR_{peak} The high-intensity group cycled at a work rate of 65% of the SRT WR_{peak} for 30 s, which was alternated by cycling for 60 s at 30% of the SRT WR_{peak}; the low- to-moderate intensity group cycled at a work rate of 45% of the SRT WR_{peak} for 30 s, which was alternated by cycling for 60 s at 30% of the SRT WR_{peak} Every 4 wk, training progression was evaluated using the SRT, and training intensity was adjusted accordingly
Meyer et al[10] (1996)	Germany	16 (16 males) Adults with chronic heart failure 54±9 y	25 W/10 s (stepwise) 3-min warm-up at 0 W Pedaling rate <60 rpm	Training intensities for the high-intensity intervals were 50% (for 30s), 70% (for 15s), and 80% (for 10s) of the baseline SRT WR_{peak}
Meyer et al[27] (1997)	Germany	18 (NR; but 18 males seems plausible) Adults with severe chronic heart failure 52±2 y	25 W/10 s (stepwise) 3-min warm-up at 0 W Pedaling rate <60 rpm	Training intensities for interval training were derived from the SRT 50% of the SRT WR_{peak} was used for the work phases The SRT was performed at the start of the study and repeated every wk to readjust training intensity
Meyer et al[28] (1996)	Germany	18 (18 males) Adults with chronic congestive heart failure 52±2 y	25 W/10 s (stepwise) 3-min warm-up at 0 W Pedaling rate <60 rpm	Training intensities for interval training were derived from the SRT 50% of the SRT WR_{peak} was used for the work phases The SRT was performed at the start of the study and repeated every wk to readjust the training intensity
Puhan et al[32] (2004)	Switzerland	98 (65 males) Adults with stage III-IV COPD 68.9±9.1 y	25 W/10 s (stepwise) 2-min warm-up at 20% of SRT WR_{peak} Pedaling rate <50 rpm or above the heart rate limit set by the normal incremental exercise test	Training intensity for an interval training program was derived from the SRT 50% of the achieved SRT WR_{peak} was used for the high-intensity intervals, whereas 10% of the SRT WR_{peak} was used for the low-intensity intervals
Puhan et al[33] (2008)	Switzerland	98 (65 males) Adults with stage III-IV COPD 68.9±9.1 y	25 W/10 s (stepwise) 2-min warm-up at 0 W Pedaling rate <50 rpm or above the heart rate limit set by the CPET	Continuous exercise training was personalized at 70% of SRT WR_{peak} Interval training was performed at 50% (high-intensity intervals) and 10% (low-intensity intervals) of the baseline SRT WR_{peak}
Strookappe et al[30] (2015)	The Netherlands	90 (59 males) Adults with sarcoidosis 47.6±11.3 y (intervention group) 49.2±10.5 y (control group)	25 W/10 s (stepwise) 3-min warm-up at 0 W Pedaling rate <60 rpm	The intensity of endurance training was personalized at 50%-60% of the baseline SRT WR_{peak}
Van Waart et al [37] (2016)	The Netherlands	230 (2 males) Adults with primary breast cancer scheduled for adjuvant chemotherapy 50.7±9.1 y	25 W/10 s (stepwise) 30-s warm-up at 25 W pedaling rate <60 rpm	The intensity of the aerobic exercise program was personalized at 50%-80% of the baseline SRT WR_{peak}
Van Wijk et al[41] (2022)	The Netherlands	26 (18 males) High-risk adults scheduled for liver or pancreatic resection 71.6±8.7 y	10 W/10 s (ramp) 2-min warm-up at 0 W voluntary exhaustion	SRT WR_{peak} was used to set up and adjust the training intensity of the high-intensity interval training and moderate intensity endurance interval training session every wk
Weemaes et al[44] (2022)	The Netherlands	185 (42 males) Adult cancer survivors 55.7±11.5 y	25 W/10 s (ramp) 3-min warm-up at 25 W Pedaling rate <60 rpm	A physical exercise training program was personalized using intervals performed alternatingly at 65% and 30% of the baseline SRT WR_{peak}

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Table 3 (*Continued*)

Authors (y)	Country	Number of Participants (Males) Study Population Age (y ± SD)	SRT Protocol Warm-Up Intensity and Duration Test Termination Criterion	Brief Description/Aim of the SRT
Application: CRF assessment				
Akkerman et al[55] (2021)	The Netherlands	24 (15 males) Children and adolescents after burns 12.6±3.6 y	Body height—dependent (ramp) 10, 15, or 20 W/10 s based on body height (<120cm, 120-150cm, or >150cm, respectively) 3-min warm-up at 25 W Pedaling rate <60 rpm	CRF was measured 4 times during the initial 6 mo after hospital discharge using the SRT Both absolute and relative WR_{peak} scores were converted into *z* scores to compare WR_{peak} scores to those of healthy peers
Drent et al[39] (2020)	The Netherlands	Total: 95 (38 males) Intervention group: 54 (28 males) Control group: 41 (10 males) Adults with sarcoidosis Median of 48 (range 26-72) y (intervention group) Median of 48 (range 29-73) y (control group)	25 W/10 s (stepwise) 3-min warm-up at 0 W Pedaling rate <60 rpm	Vo_{2peak} as main variable was measured during the SRT protocol with respiratory gas analysis measurements SRT WR_{peak} was used to estimate CPET Vo_{2peak} using the prediction equation of De Backer[23] CRF was assessed at baseline and follow-up (3 mo later)
Luthi et al[38] (2018)	Switzerland	565 (NR) Adults with chronic musculoskeletal pain Not reported for subgroup, but for total group: 43±12 y	25 W/10 s (stepwise) 2-min warm-up at 0 W Pedaling rate <60 rpm	The SRT was performed as an indicator of CRF 2-3 d after admission and 2-3 d before discharge (after 4-5 wk of a therapeutic program)
Mensink-Bout et al[53] (2022)	The Netherlands	478 (NR) Healthy adolescents Not reported for subgroup, but for total group: 13.5 (13.1-14.6) y*	Body height—dependent (ramp) 10, 15, or 20 W/10 s based on body height (<120cm, 120-150cm, >150cm, respectively) 3-min warm-up at 25 W pedaling rate <60 rpm	Absolute SRT WR_{peak} was converted into a z score and divided by the predicted SRT WR_{peak} based on sex- and age-related Dutch norm values to express SRT performance as a percentage of predicted
Oliveira et al[54] (2017)	United Kingdom	54 (31 males) Healthy adolescents 13.1±0.8 y	Body height—dependent (ramp) 10, 15, or 20 W/10 s based on body height (<120cm, 120-150cm, >150cm, respectively) 3-min warm-up at 25 W pedaling rate <60 rpm	SRT WR_{peak} was used to estimate Vo_{2peak}
Puhan et al[33] (2008)	Switzerland	98 (65 males) Adults with stage III-IV COPD 68.9±9.1 y	25 W/10 s (stepwise) 2-min warm-up at 0 W Pedaling rate <50 rpm or above the heart rate limit set by the normal incremental exercise test	Group 1 performed continuous exercise training with a target work rate of 70% of SRT WR_{peak} Group 2 performed interval training at 50% (high-intensity intervals) and 10% (low-intensity intervals) of SRT WR_{peak} SRT WR_{peak} was 1 of the 4 tests used to estimate change in CRF
Strookappe et al[30] (2015)	The Netherlands	90 (59 males) Adults with sarcoidosis 47.6±11.3 y (intervention group) 49.2±10.5 y (control group)	25 W/10 s (stepwise) 3-min warm-up at 0 W Pedaling rate <60 rpm	SRT WR_{peak} was used to estimate Vo_{2peak} using the prediction equation of De Backer[23]
Strookappe et al[29] (2016)	The Netherlands	146 (89 males) Adults with sarcoidosis 47.1±11.2 y	25 W/10 s (stepwise) 2-min warm-up at 0 W Pedaling rate <60 rpm	SRT WR_{peak} was used to estimate Vo_{2peak} using the prediction equation of De Backer[23]
Weemaes et al[44] (2022)	The Netherlands	185 (42 males) Adult cancer survivors 55.7±11.5 y	25 W/10 s (ramp) 3-min warm-up at 25 W Pedaling rate <60 rpm	An indication of CRF was assessed using the SRT, 6MWT, and CPET

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Table 3 (*Continued*)

Authors (y)	Country	Number of Participants (Males) Study Population Age (y ± SD)	SRT Protocol Warm-Up Intensity and Duration Test Termination Criterion	Brief Description/Aim of the SRT
Application: CRF assessment as part of preoperative risk assessment				
Cuijpers et al[52] (2022)	The Netherlands	238 (134 males) Adults diagnosed with colorectal cancer and scheduled for elective resection 69.3±9.9 y	10 W/10 s (ramp) 2 min warm-up at 0 W Pedaling rate <60 rpm	SRT WR_{peak} values (in W and in W/kg) were used as an indicator of the patient's preoperative CRF The association between preoperative SRT performance postoperative outcomes was determined
Cuijpers et al[51] (2022)	The Netherlands	256 (145 males) Adults scheduled for elective colorectal cancer surgery 69.4±10.0 y	10 W/10 s (ramp) 2-min warm-up at 0 W Pedaling rate <60 rpm	SRT WR_{peak} values (in W and in W/kg) were used as an indicator of the patient's preoperative CRF The association between preoperative SRT performance postoperative outcomes was determined
Janssen et al[49] (2021)	The Netherlands	77 (56 males) Adults scheduled for elective 1- to 3-level lumbar spinal fusion 58.8±10.3 y	25 W/10 s (ramp) 2-min warm-up at 0 W Pedaling rate <60 rpm	SRT WR_{peak} values (in W and in W/kg) were used as an indicator of the patient's preoperative CRF The association between preoperative SRT performance postoperative outcomes was determined
Janssen et al[50] (2022)	The Netherlands	49 (14 males) Adults who underwent lumbar spinal fusion 61.3±11.9 y	25 W/10 s (ramp) 2-min warm-up at 0 W Pedaling rate <60 rpm	SRT WR_{peak} values (in W and in W/kg) were used as an indicator of the patient's preoperative CRF The association between preoperative SRT performance postoperative outcomes was determined
Janssen et al[31] (2022)	The Netherlands	52 (39 males) Adults who underwent an invasive Ivor-Lewis esophagectomy and received a fully standardized enhanced recovery after surgery program 64±8 y	25 W/10 s (stepwise) 3-min warm-up at 0 W Pedaling rate <60 rpm or by the patient's request	The SRT was used to estimate VO_{2peak}
Van Beijsterveld et al[47] (2019)	The Netherlands	96 (60 males) Adults undergoing hepatic resection for benign or malignant tumors 65.0±12 y	10 W/10 s (ramp) 2-min warm-up at 0 W Pedaling rate <60 rpm	SRT WR_{peak} values (in W and in W/kg) were used as an indicator of the patient's preoperative CRF The association between preoperative SRT performance postoperative outcomes was determined
Van Beijsterveld et al[48] (2020)	The Netherlands	63 (31 males) Adults undergoing elective pancreatic resection 68 (range 26-85) y	10 W/10 s (ramp) 2-min warm-up at 0 W Pedaling rate <60 rpm	SRT WR_{peak} values (in W and in W/kg) were used as an indicator of the patient's preoperative CRF The association between preoperative SRT performance postoperative outcomes was determined

Abbreviations: NR, not reported.
* 2.5^{th}-97.5^{th} percentile.

Assessment of cardiorespiratory fitness

In 6 studies, the SRT was used to estimate CRF once in adolescents (n=4854),[53,54] adults with sarcoidosis (n=300),[29,30,39] and adults with chronic musculoskeletal pain (n=891).[38] In 2 studies,[33,44] the SRT was used to evaluate CRF before and after a physical exercise training program in adults with severe COPD (n=98)[33] and in adult cancer survivors (n=185).[44] In 1 study,[55] the SRT was used to monitor the course of CRF over time in children and adolescents after burns (n=24) who performed the SRT 4 times during the initial 6 months after hospital discharge.

Interpretation of test results differed between studies. In 5 studies,[29,30,38,39,54] SRT WR_{peak} was entered into a prediction equation to estimate Vo_{2peak}. In 2 studies, including children and adolescents with burns[55] or asthma,[53] relative WR_{peak} values were compared to existing norm values by calculating z-scores. In 2 other studies,[33,44] SRT WR_{peak} was used as the primary outcome measure and was monitored over time within individual patients.

Preoperative assessment of cardiorespiratory fitness

In 7 studies, the SRT was used for preoperative assessment of CRF in various patient populations scheduled for major surgery, including adults undergoing elective hepatic resection (n=96),[47] pancreatic resection (n=63),[48] lumbar spinal fusion (n=126),[49,50] esophagectomy (n=52),[31] or colorectal cancer surgery (n=494).[51,52] These studies were performed in The Netherlands. In 6 of them,[31,47-49,51,52] the relationship between preoperative SRT performance and postoperative outcomes (eg, complications, time to recovery of physical functioning) was investigated. Better preoperative SRT performance was consistently associated with more favorable surgical outcomes. In 1 study,[50] the SRT was used to develop preoperative risk profiles of patients. These risk profiles were established based on smoking status, health-related quality of life, mobility, flexibility of the lumbar spine, motor control, and SRT performance. Results showed that patients who were classified as "fit" had a significantly shorter length of stay in the hospital and a shorter time to functional recovery compared to patients who were classified as "deconditioned."[50]

Personalizing high-intensity interval training

In 12 studies, the SRT was used to develop high-intensity interval training programs for adults with chronic heart failure (n=92),[10,27,28,34,36] adults with cancer and adult cancer survivors (n=613),[35,37,44] adults with severe COPD (n=196),[32,33] adults with sarcoidosis (n=90),[30] and adults undergoing elective liver or pancreatic resection (n=26).[41] The SRT was used to personalize the intensity of the high- and low-intensity intervals of a physical exercise interval training program, in which 50%-80% of the SRT WR_{peak} was used for the high-intensity intervals (ranging from 10-40s) and 10%-30% of the SRT WR_{peak} was used for the low-intensity intervals (ranging from 30-60s) (online supplementary file 2). In 6 studies,[27,28,34,35,41,56] high- and low-intensity interval intensities were adjusted every 1, 4, or 6 weeks based on SRT performance. In 2 studies,[30,44] interval intensities were adjusted based on the RPE score, whereas in 1 study interval intensity was adjusted based on heart rate.[32] In the other studies,[10,33,36,37] interval training intensities were not adjusted during the training period.

Discussion

The aim of this scoping review was to provide an overview of the clinimetric properties of the SRT to assess CRF, describe its underlying physiological responses, and summarize the various applications of the SRT in current clinical and research practice. Results indicate that the SRT is a practical short-term maximal exercise test that is reliable and valid for assessing CRF in various pediatric and adult populations, both those with and without morbidities. The quality of this evidence was considered moderate to high (online supplementary file 1, table 3). Because of its short supramaximal nature, physiological parameters generally indicate that the SRT puts a smaller burden on the cardiopulmonary system compared to CPET. The SRT is currently applied in various clinical settings, primarily for CRF assessment and/or to personalize the intensity of interval training programs.

A plethora of evidence has demonstrated the importance of CRF as a health indicator. As such, assessing CRF can be appreciated in all phases of clinical decision-making, including diagnosis, assessment of severity, disease progression, prognosis, and response to treatment.[8] As CPET is often not feasible in clinical practice, alternative (sub)maximal exercise tests have been used to estimate CRF, such as the 6-minute walk test (6MWT), incremental shuttle walk test (iSWT), and Astrand test. Regarding criterion validity, walking distance at the 6MWT was weakly to strongly correlated with CPET Vo_{2peak} (*r* values ranging from .51-.67,[57] from .28-.88,[57] and from .46-.64[58] in adults with COPD, adults with heart failure, and in healthy adults, respectively). Walking distance at the iSWT was moderately to strongly correlated with CPET Vo_{2peak} achieved during cycle and treadmill testing (*r* values ranging from .72-.81 and from .78-.88, respectively) in adults with COPD.[59] Vo_{2peak} estimated from the Åstrand test was moderately to strongly correlated with CPET Vo_{2peak} (*r* values ranging from .78-.95) in various healthy and sick populations.[60] However, some studies reported an overestimation of Vo_{2peak} from the Åstrand test (values ranging from 3%-21%),[60] while others reported an underestimation (values ranging from 4%-27%)[60,61] compared to the measured CPET Vo_{2peak}. Compared to the abovementioned alternative exercise tests, SRT WR_{peak} demonstrated superior criterion validity to assess CRF, with *r* values ranging from .771-.958. Test-retest reliability of the 6MWT (ICC values ranging from .82-.99)[57] and iSWT (ICC values ranging from .83-.92)[62] are comparable to the SRT (ICC values ranging from .908-.996). Besides superior validity to assess CRF, the SRT has some practical advantages over the abovementioned exercise tests. For example, the SRT has no ceiling effect in relatively fit participants and can be used to set up, monitor, and adjust personalized interval training programs. A potential limitation of the SRT is that participants should be able to sit and pedal on a cycle ergometer. For walking tests, however, patients need to be able to walk independently, which makes the test less safe in vulnerable populations (ie, fall risk). Another potential limitation of the SRT is that participants should be able and willing to exert maximum effort for a valid SRT performance, which is similar to other maximal exercise tests.

An important strength of the SRT compared to CPET is that physiological responses indicate that the SRT puts a smaller burden on the cardiopulmonary system, despite the fact that SRT WR_{peak} exceeds CPET WR_{peak} by, on average, 79% (supramaximal work rate). This is indicated by the, on average, 5.3% and 8.3% lower values for HR_{peak} and VE_{peak}, respectively, achieved at the SRT compared to CPET. In line with this, our own clinical experiences indicate that leg muscle fatigue is most often reported as the reason why the participant can no longer maintain pedaling against the rapidly increasing work rate. RPE values at peak exercise were also lower for the SRT compared to CPET in the majority of the studies, indicating a lower perceptual test burden. Another important strength is the fact that the SRT involves a practical short-term exercise test that requires only a cycle ergometer. Therefore, the SRT can be applied in a variety of settings, including non-university hospitals, primary care, and even in community- and home-based settings, while CPET is often available only in university medical centers and research settings. Despite these practical advantages, it is important to realize that the SRT cannot replace CPET in all circumstances, as the SRT does not provide any diagnostic information. Therefore, it cannot be used to determine which organ system is responsible for limiting exercise tolerance (eg, cardiovascular, pulmonary, peripheral), and it is also not suitable to identify potential contraindications for physical exercise training. Furthermore, if the participant is not able or not willing to perform at maximal effort, test results of the SRT should be interpreted with caution, while CPET also yields submaximal outcome measures that can be used as an indication of CRF (eg, oxygen uptake at the ventilatory anaerobic threshold, oxygen uptake efficiency slope).

The SRT has already been applied in various healthy and patient populations and in various settings; the SRT protocol used slightly differed across studies, significant protocol adaptations were needed to make the test suitable for the target population, and the SRT results were interpreted in various ways. For comparison purposes, uniformity should be reached regarding the SRT protocol used and the terminology. Based on the current knowledge, the recommended SRT protocol consists of a 3-minute unloaded warm-up phase, followed by a work increment phase, when the work rate is rapidly increased by 25 Watts each 10 seconds—that is, ideally preprogrammed in the cycle ergometer in a ramp-like manner (eg, 5W/2s; fig 2, graph B). Work rate increments should continue until peak exercise, which is defined as the point at which the participant can no longer maintain a pedaling frequency ≥60 rpm, despite strong verbal encouragement. A maximal effort is essential for adequate interpretation of the SRT results. As such, careful pretest instructions about the purpose of the test, the test protocol, and the importance of maximal effort are vital. Alternative protocols are recommended for children <18 years[43] (10W/10s, 15W/10s, or 20W/10s, depending on body height; fig 2, graph C) or in unfit and/or older adult patients[63] (10W/10s; fig 2, graph D).

In children, adolescents, and young adults, the available norm values were frequently used for interpretation of SRT performance.[43,46] Because of a lack of norm values for adults and elderly, a prediction equation is frequently used to evaluate their CRF. In these prediction equations, SRT WR_{peak} is used to estimate VO_{2peak}, which can subsequently be compared to norm values. A drawback of equations to predict VO_{2peak} from alternative exercise tests is their prediction error. The conversion to VO_{2peak} might be of less interest when sex- and age-related norm values for SRT WR_{peak} are also available for adults and elderly.

Implications for future research

Although the SRT is recommended as a short-term practical exercise test to assess CRF, the test does not seem to be widely applied in clinical practice. A possible explanation is the current lack of norm values for healthy adults and elderly. To facilitate test interpretation, it is, therefore, recommended to collect an adequate set of sex- and age-related norm values for SRT WR_{peak} in healthy adults, including elderly. Another possible explanation for the underuse of the SRT might be the unfamiliarity of both health care professionals and clinical researchers with the SRT as an alternative to CPET to assess CRF. Besides insight into its applications and clinimetric properties, more in-depth examination of the underlying physiological responses and safety of the SRT is warranted. To evaluate the use or nonuse of the SRT among physical therapists, exercise physiologists, and other professionals involved in (clinical) exercise testing, a survey might provide relevant data.

Study limitation

Because this was a scoping review, only a quality appraisal was performed for the studies evaluating clinimetric properties of the SRT.

Conclusions

The SRT is a practical short-term maximal exercise test that can be used for CRF assessment in various healthy and patient populations while placing a lower burden on the cardiopulmonary system compared to CPET. Its validity, test-retest reliability, and responsiveness were considered to be sufficient to recommend the SRT for CRF assessment and monitoring. This finding, in combination with its potential applications, make the SRT promising for widespread implementation of CRF assessment in both clinical and research practice, as well as for personalizing training intensity and monitoring longitudinal changes in CRF. However, the SRT cannot replace CPET, because it does not provide diagnostic information. Moreover, the lack of norm values for SRT performance in adults and elderly currently limits the interpretation of test results.

Suppliers

a. Rayyan; Rayyan Systems Inc.

Keywords

Aerobic fitness; Exercise test; Prehabilitation; Physical fitness; Rehabilitation; Test properties

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Appendix A. Search 18-07-2023

PubMed

(“Cardiorespiratory Fitness”[Mesh] OR “Physical Fitness”[Mesh] OR “Exercise Test”[Mesh] OR “Exercise Tolerance”[Mesh] OR “cardiorespiratory fitness” OR “CRF” OR “physical fitness” OR “exercise test*” OR “exercise tolerance” OR “aerobic fitness” OR “exercise capacity”) AND (“steep ramp test” OR “steep ramp anaerobic test” OR “SRT” OR “SRAT”)

AND

(English[Language]) OR (Dutch[Language])

Hits: 161

Cochrane Library

ID	Search
#1	([“steep ramp test” OR “steep ramp anaerobic test” OR “SRT” OR “SRAT” OR “Extended steep ramp”]):ti,ab,kw
#2	([“cardiorespiratory fitness” OR “CRF” OR “physical fitness” OR “exercise test*” OR “exercise tolerance” OR “aerobic fitness” OR “Exercise capacity”]):ti,ab,kw
#3	MeSH descriptor: [Cardiorespiratory Fitness] explode all trees
#4	MeSH descriptor: [Physical Fitness] explode all trees
#5	MeSH descriptor: [Exercise Test] explode all trees
#6	(#1 AND #2) AND (#3 OR #4 OR #5)

Hits: 17

PsycINFO
S1: MM physical fitness

Search string:

(steep ramp test OR SRT OR steep ramp anaerobic test OR SRAT) AND (cardiorespiratory fitness OR physical fitness OR exercise test OR exercise tolerance OR aerobic fitness OR exercise capacity OR exercise OR #s1)

Filter: English

Hits: 47
CINAHL Complete

#1 MM Physical Fitness
#2 MM Cardiorespiratory Fitness
#3 MM Exercise Test
#4 MM Exercise Tolerance

Search string:

(steep ramp test OR SRT OR steep ramp anaerobic test OR SRAT) AND (cardiorespiratory fitness OR physical fitness OR exercise test OR exercise tolerance OR aerobic fitness OR exercise capacity OR exercise OR #s1 OR #s2 OR #s3 OR #s4)

Filter: English

Hits: 88

Embase

(‘cardiorespiratory fitness’ OR ‘CRF’/exp OR ‘CRF’ OR ‘physical fitness’/exp OR ‘physical fitness’ OR ‘exercise test*’ OR ‘exercise tolerance’ OR ‘aerobic fitness’/exp OR ‘aerobic fitness’ OR ‘exercise capacity’/exp OR ‘exercise capacity’ OR ‘cardiorespiratory fitness’/exp OR ‘fitness’/exp OR ‘exercise test’/exp OR ‘exercise tolerance’/exp) AND (‘steep ramp test’ OR ‘steep ramp anaerobic test’ OR ‘extended steep ramp’ OR ‘steep ramp’:ti,ab OR ‘extended steep ramp’:dn,ti,ab OR ‘steep ramp’)

Filter: English

Hits: 54

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