Anaerobic exercise testing in rehabilitation

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Published in:
Journal of Rehabilitation Medicine

DOI:
10.2340/16501977-2213

Publication date:
2017

J Rehabil Med 2017; 49: 289–303

REVIEW ARTICLE

ANAEROBIC EXERCISE TESTING IN REHABILITATION: A SYSTEMATIC REVIEW OF AVAILABLE TESTS AND PROTOCOLS

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Objective: **Anaerobic capacity assessment in rehabilitation has received increasing scientific attention in recent years. However, anaerobic capacity is not tested consistently in clinical rehabilitation practice. This study reviews tests and protocols for anaerobic capacity in adults with various disabilities (spinal cord injury, cerebral palsy, cerebral vascular accident, lower-limb amputation(s)) and (able-bodied) wheelchair users.**

Data sources: **PubMed, CINAHL and Web of Science.**

Study selection: **Papers were screened by 2 independent assessors, and were included when anaerobic exercise tests were performed on the above-selected subject groups.**

Data extraction: **Included articles were checked for methodological quality.**

Data synthesis: **A total of 57 papers was included. Upper-body testing [56 protocols] was conducted with arm crank [16] and wheelchair tests [40]. With a few [2] exceptions, modified Wingate (Wingate) protocols and wheelchair sprint tests dominated upper-body anaerobic testing. In lower-body anaerobic work [11], bicycle [3] and recumbent [1], and overground tests [7] were used, in which Wingate, sprint or jump protocols were employed.**

Conclusion: **When equipment is available a Wingate protocol is advised for assessment of anaerobic capacity in rehabilitation. When equipment is not available a 20–45 s sprint test is a good alternative. Future research should focus on standardized tests and protocols specific to different disability groups.**

Key words: anaerobic capacity; exercise; rehabilitation; review; Wingate; wheelchair; patients.

Accepted Jan 20, 2017; Epub ahead of print Mar 28, 2017

J Rehabil Med 2017; 49: 289–303

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In 2011, 15% of the world's population was estimated to be living with a disability. Approximately 2.2% of the world's population was limited in functioning to a significant degree (1). Within the International Classification of Functioning, Disability and Health (ICF) model, physical capacity quantifies the ability to perform bodily functions and activities of daily living, and to participate (2). Today, it is deemed increasingly important to monitor and systematically evaluate physical capacity in persons with a disability or chronic disease in clinical rehabilitation and beyond (3, 4). Monitoring changes in physical capacity may give an indication of the effectiveness of training and rehabilitation programmes, as well as of developing a physically active lifestyle (5–7).

Physical capacity, defined as the physiological ability to perform activities of daily living and leisure, can be expressed by aerobic capacity, anaerobic capacity, muscle force, flexibility and balance (8). Short bursts of exercise are dominated by the anaerobic system, while energy in activities longer than 30–45 s is primarily generated by the aerobic system (9, 10). Aerobic capacity is the ability to deliver oxygen to muscles, and to utilize it to generate energy during prolonged exercise. Anaerobic capacity is the short-term ability to generate energy by metabolizing creatine phosphate and by glycolysis, without using oxygen, whereby lactate accumulates.

In clinical rehabilitation practice, muscle force, flexibility and balance are frequently monitored, whereas aerobic capacity is measured occasionally. However, in physically disabled individuals most motor activities of daily living are of short duration and therefore utilize anaerobic metabolism (11). Furthermore, performing activities of daily living in these individuals produces relatively high physical strain (12) in the context of an often reduced physical capacity. Since most motor activities of daily living utilize the anaerobic metabolism (11), it is essential to also test anaerobic capacity in physically disabled individuals.

Anaerobic energy production can be determined by muscle biopsies in which the increase in muscle lactate and the decrease in creatine phosphate concentration are measured (13). Measuring blood lactate can give an indication of anaerobic metabolism (14); however, this invasive method does not directly measure anaerobic capacity. Historically, there has not been a single laboratory measurement that directly determines anaerobic work (15). In practice, anaerobic capacity has been mostly determined by measuring the rate of work performed under circumstances in which the aerobic

 ISSN 1650-1977 doi: 10.2340/16501977-2213

metabolism is assumed to contribute very little, which is in tests with a short duration. However, both aerobic and anaerobic processes were found to contribute significantly during intense exercise lasting 30 s to 3 min (13). This makes it impossible to strictly determine either aerobic or anaerobic capacity by measuring the rate of work during field tests, thus limiting their validity.

In able-bodied people, anaerobic capacity is commonly tested using a 30 s Wingate Anaerobic bicycle test (WAnT), which is feasible, reliable and valid (16). One can imagine that the protocol of the commonly used 30 s WAnT is not feasible for most physically disabled individuals, because of, for instance, reduced capacity in the lower extremities, or the relatively higher physical strain of activities (12). In physically disabled people a diversity of tests and protocols for anaerobic capacity are foreseen in the context of upper- or lower-body work capacity and the wide variation of physical abilities.

In a previous non-systematic review, protocols for testing anaerobic capacity in individuals using wheelchairs were investigated (11). From this review it became clear that WAnT, with a variety of protocols and types of ergometers, was generally performed to assess anaerobic capacity. Furthermore, the study suggested that test devices should be specific to the everyday propulsion mode of participants in either daily life or sport activities. However, this review was not systematic, and it focussed only on wheelchair users (17).

Given the clinical importance of the assessment of anaerobic capacity in different rehabilitation groups, guidelines for testing anaerobic capacity are required. With the lack of an up-to-date systematic overview of the scientific literature, the current study aimed to systematically review international literature on tests and protocols for anaerobic capacity in specific groups of people with a disability (spinal cord injury (SCI), cerebral vascular accident (CVA), lower-limb amputation, adults with cerebral palsy (CP), and wheelchair users). Based on this overview, suggestions and implications for clinical use and continued research are provided.

METHODS

Search strategy

Electronic database searches were conducted using PubMed, CINAHL and Web of Science. No time and language restrictions were used. A combination of the free text words "anaerobic capacity, performance, power, test, sprint performance, spinal cord injury, cerebrovascular accident, cerebral palsy, amputation and wheelchair" were used using Booleans (OR/AND). When possible, SCI, CVA, and CP were used as a MeSH term. Since MeSH terms were not supported by Web of Science, the free text word "stroke" was added to the search strategy. The exact search strategies are shown in Appendix S1[1]. The final search was performed on 28 June 2016.

Study selection

After removing duplicates, title/abstract screening was performed using the following inclusion criteria: subjects were patients with SCI and/or CVA/stroke and/or lower-limb amputation and/or CP and/or wheelchair users (also able-bodied); anaerobic capacity was measured; and the study involved primary research. Articles were excluded when they met at least one of the following exclusion criteria: age < 18 years; anaerobic capacity was derived from an aerobic capacity test; stroke was used in relation to meanings other than CVA (for instance: swimming, rowing, propulsion technique, cardiac output); the paper was about anaerobic bacteria or antibiotics; and animal studies. During full-text screening the set of title and abstract inclusion criteria was extended by the following criteria: description of the protocol was available; outcome parameters were defined; when the study population consisted of patients, impairment was reported; and the study was published as a full paper. It was decided to also include studies on able-bodied wheelchair users because of the small amount of available literature on rehabilitation patients.

The definition of anaerobic capacity, as used in inclusion criterion 2 was further specified, using the following criteria. If only performance time was measured, activities with a duration (mean−1 standard deviation; SD) of less than 45 s were included. In case of repeated sprints, work-rest ratios had to be less than 1. Tests were not allowed to contain agility elements. Finally, studies that did not fulfil one of these criteria, but in which the authors stated that anaerobic capacity was measured, were included.

During full-text screening, the same exclusion criteria as used in title and abstract screening were applied. Articles were included when all of the inclusion criteria and none of the exclusion criteria were met. Title, abstract and full-text screenings were conducted by 2 independent assessors (L.A.K. and T.A.). After independent assessment, papers with disagreement among assessors were discussed during a consensus meeting. When no consensus could be reached, a third assessor (J.M.H.) decided whether the study would be included. Inter-observer agreement, expressed as Cohen's kappa, was calculated for both the title/abstract assessment and the full-text assessment.

Quality assessment

All selected articles were scored on methodological quality using the McMaster Critical Review Form for Quantitative studies (18). Following the items of this checklist, articles were assessed on their purpose, literature background, design, sample, outcomes, intervention, result, drop-outs, conclusion and implication. The outcome of this evaluation for each item resulted in "yes" (meets criterion), "no" (does not meet criterion), or "n.a." (not applicable). Based on the insights of the authors, the possibilities in item 3 were expanded by "validity/reliability study", since this type of study did not match any of the suggested designs. When a study had more than one purpose, different designs can be noted. Items 8 and 9 were only scored "yes" when the reliability or validity of all protocols measuring anaerobic capacity was mentioned or investigated in the tested population. A sum score of at least 7 indicated sufficient methodological quality (19). Throughout this systematic review Prisma Statements were followed (20).

[1]http://www.medicaljournals.se/jrm/content/?doi=10.2340/16501977-2213

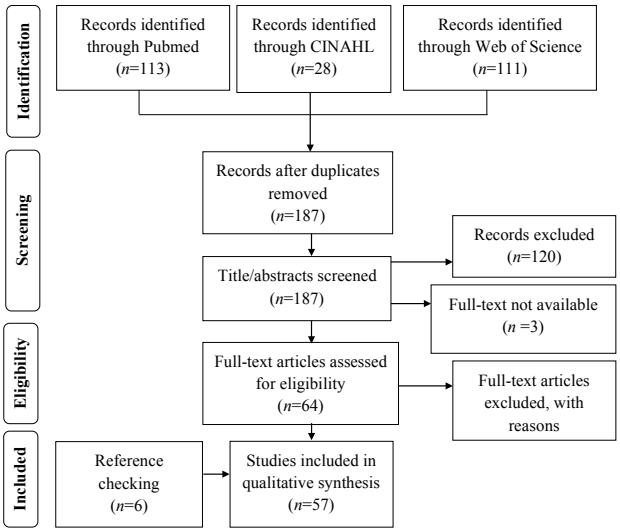

Fig. 1. Flowchart of data search.

RESULTS

Study material

After removing duplicates 187 articles were found. After title/abstract assessment, 64 articles met the criteria, of which 51 papers were included after full-text assessment. Some studies were excluded based on more than one criterion. Thirteen articles were excluded because anaerobic capacity was not measured (number of studies (n)=7), impairment was not mentioned (n=2), study was not published as full paper (n=7), study population was younger than 18 years (n=1) or anaerobic capacity was derived from aerobic test (n=2). Three full-text versions of the articles were not available and were excluded. By reference checking 6 additional papers were included, whereby a total of 57 papers were included in this systematic review (Fig. 1).

High inter-observer absolute agreement was found for title/abstract assessment (Cohen's kappa=0.91) and full-text assessment (Cohen's kappa=0.98). Table I shows the methodological quality of the included papers. Thirty-one of 57 studies were cross-sectional. Five studies were randomized controlled trials, which is considered the most vigorous research design (18). The reliability of the tests and protocols was described in 13 studies, whereas the validity for the tested population was described in 5 studies. Except for 3 studies methodological quality of all included studies was sufficient. The details of the quality assessment of the included studies are given in Table I.

In total, 67 protocols were found in this review, which were highly variable on for instance test mode, duration (5–70 s), resistance and initial velocity (0 to maximum velocity). Table II describes characteristics of the tested populations, in order to explain feasible tests for specific populations. Parameters of the protocols that can assist in providing guidelines for clinical use and research, as for instance duration, warming up and resistance, are described in Table III. Throughout the Results section findings were structured based on the distinction between upper- and lower-body anaerobic assessment, in which the different tests are described for the devices used. The other properties of the protocols are described within this structure (Table III), and are considered in the Discussion.

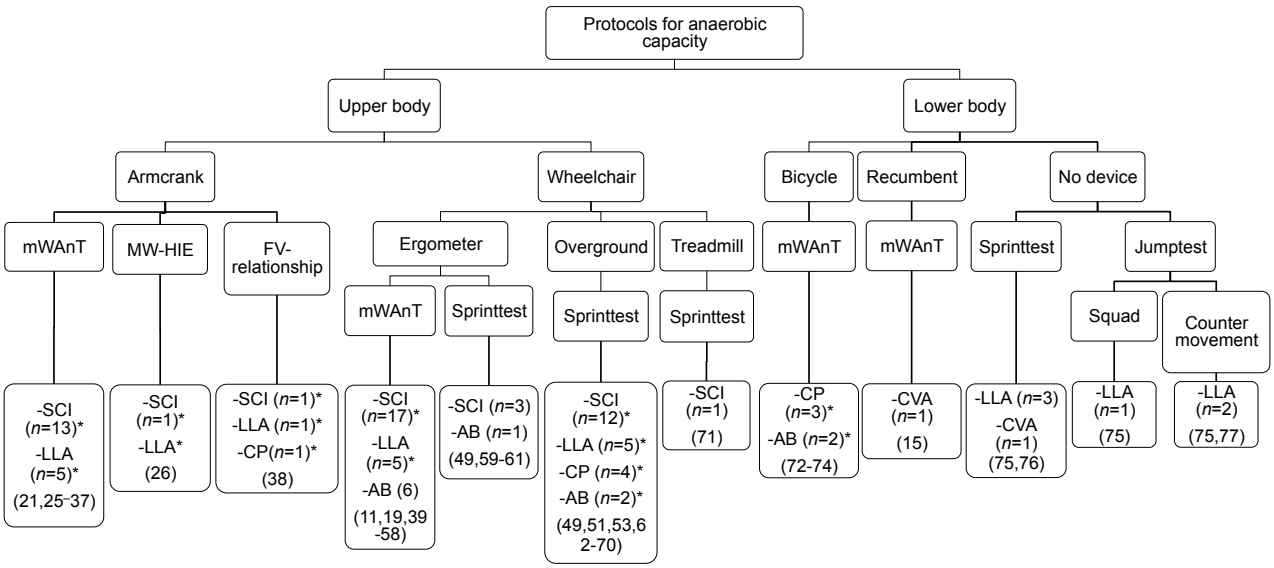

Fig. 2. Systematic description of the protocols used for measuring anaerobic capacity, as found in this systematic review. SCI: spinal cord injury; LLA: lower-limb amputation; CP: cerebral palsy; AB: able-bodied. *Test study population consisted of people with different physical disabilities. Between bracelets: number of protocols. For an extended description of the test population, see Table II.

Table I. Detailed methodological quality scores of the included studies following McMasters Critical Review Form for Quantitative studies (18)

Study, ref	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total
12	Yes	Yes	CS	44	Yes	No	No	No	na	na	No	Yes	Yes	Yes	Yes	Yes	9
17	Yes	Yes	CS	50	Yes	No	No	No	na	na	Yes	Yes	Yes	Yes	No	Yes	8
21	Yes	Yes	CS	8	Yes	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	7
22	Yes	Yes	CS	75	Yes	Yes	No	No	na	na	No	Yes	Yes	Yes	No	Yes	9
23	Yes	Yes	BA	24	Yes	No	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	9
24	Yes	Yes	CS	17	Yes	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	8
25	Yes	Yes	CS	9	Yes	No	No	No	na	na	No	Yes	Yes	No	No	Yes	6
26	Yes	Yes	RCT	18	Yes	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	11
27	Yes	Yes	RV	45	Yes	No	Yes	No	na	na	Yes	Yes	Yes	Yes	No	Yes	10
28	Yes	Yes	CS	39	Yes	No	No	No	na	na	No	Yes	Yes	Yes	Yes	Yes	9
29	Yes	Yes	RV	43	Yes	No	Yes	No	na	na	Yes	Yes	Yes	Yes	Yes	Yes	11
30	Yes	Yes	RCT	11	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	11
31	Yes	Yes	CS	31	Yes	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	8
32	Yes	Yes	BA	7	Yes	Yes	Yes	No	Yes	na	No	Yes	Yes	Yes	Yes	Yes	12
33	Yes	Yes	CS	28	Yes	No	No	No	na	na	No	Yes	Yes	No	No	Yes	6
34	Yes	Yes	CS	34	Yes	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	7
35	Yes	Yes	CS	17	Yes	No	No	No	na	na	No	Yes	Yes	No	No	Yes	7
36	Yes	Yes	BA	6	Yes	No	No	No	Yes	na	No	Yes	Yes	Yes	No	Yes	8
37	Yes	No	CS	6	Yes	No	Yes	No	na	na	No	No	Yes	No	No	Yes	6
38	Yes	Yes	BA	19	Yes	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	8
39	Yes	Yes	C	20	Yes	No	No	No	na	na	No	Yes	Yes	Yes	Yes	Yes	9
40	Yes	Yes	CS	23	Yes	No	No	No	na	na	No	Yes	Yes	No	No	Yes	7
41	Yes	Yes	BA	28	Yes	Yes	Yes	No	Yes	na	No	Yes	Yes	Yes	Yes	Yes	11
42	Yes	Yes	CS	11	Yes	Yes	No	Yes	na	na	No	Yes	Yes	Yes	Yes	Yes	10
43	Yes	Yes	RV	20	Yes	Yes	Yes	Yes	na	na	No	Yes	Yes	No	No	Yes	10
44	Yes	Yes	CS	44	Yes	No	No	No	na	na	No	Yes	Yes	Yes	Yes	Yes	9
45	Yes	Yes	CS	166	Yes	Yes	No	No	na	na	No	Yes	Yes	Yes	No	Yes	9
46	Yes	Yes	RV/CS	7	Yes	Yes	Yes	No	na	na	No	Yes	Yes	No	Yes	Yes	11
47	Yes	Yes	CS	9	Yes	Yes	No	No	na	na	No	Yes	Yes	Yes	No	Yes	9
48	Yes	Yes	RV	46	Yes	Yes	Yes	Yes	na	na	No	Yes	Yes	Yes	No	Yes	11
49	Yes	Yes	RCT	25	Yes	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	11
50	Yes	Yes	CS	19	Yes	No	No	No	na	na	No	Yes	Yes	Yes	Yes	Yes	9
51	Yes	Yes	RCT	27	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	12
52	Yes	Yes	CS	67	Yes	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	8
53	Yes	Yes	CS	67	Yes	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	8
54	Yes	Yes	CS	19	Yes	No	No	No	na	na	No	Yes	Yes	No	No	Yes	7
55	Yes	Yes	RV/BA	10	Yes	Yes	No	No	Yes	na	Yes	Yes	Yes	Yes	No	Yes	11
56	Yes	Yes	CS	8	Yes	No	No	No	na	na	na	Yes	Yes	Yes	No	Yes	7
57	Yes	Yes	SC	1	Yes	na	Yes	No	na	na	na	Yes	Yes	Yes	No	Yes	9
58	Yes	Yes	BA	15	Yes	No	Yes	No	Yes	na	No	Yes	Yes	Yes	No	Yes	10
59	Yes	Yes	CS	52	Yes	Yes	Yes	No	na	na	na	Yes	Yes	Yes	Yes	Yes	9
60	Yes	Yes	RV	19	Yes	No	Yes	No	na	na	na	Yes	Yes	Yes	No	Yes	8
61*	Yes	Yes	RV/CS	50	Yes	No	No	No	na	na	No	Yes	Yes	No	Yes	Yes	8
62	Yes	Yes	CS	29	Yes	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	8
63	Yes	Yes	BA	13	Yes	No	No	No	Yes	na	No	Yes	Yes	Yes	No	Yes	8
64	Yes	Yes	BA	14	Yes	No	No	No	Yes	na	Yes	Yes	Yes	Yes	No	Yes	9
65	Yes	Yes	CS	16	Yes	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	8
66	Yes	Yes	RCT	12	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	10
67	Yes	Yes	BA	21	Yes	No	No	No	na	na	No	Yes	Yes	No	No	Yes	7
68*	Yes	Yes	C	80	No	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	7
69	Yes	Yes	CS	41	Yes	No	No	No	na	na	No	Yes	Yes	Yes	No	Yes	8
70	Yes	Yes	RV	20	Yes	No	Yes	No	na	na	No	Yes	Yes	Yes	Yes	Yes	10
71	Yes	Yes	CS	21	Yes	No	No	Yes	na	na	No	Yes	Yes	Yes	No	Yes	8
72	Yes	Yes	RV	28	Yes	Yes	Yes	Yes	na	na	No	Yes	Yes	Yes	No	Yes	11
73	Yes	Yes	CS	15	Yes	Yes	No	No	na	na	No	Yes	Yes	No	No	Yes	8
74	Yes	Yes	SC	1	Yes	na	No	No	Yes	na	na	Yes	Yes	No	No	Yes	7
75	Yes	No	CS	12	Yes	No	No	No	na	na	na	Yes	Yes	Yes	No	Yes	7

1: Was the purpose stated clearly?
2: Was relevant background literature reviewed?
3: What was the design of the study?
4: What was the sample size of the study?
5: Was the sample described in detail?
6: Was the sample size justified?
7: Were the outcome measures of the anaerobic test reliable for the specific study population? (if not described assume no.)
8: Were the outcome measures of the anaerobic test valid for the specific study population? (if not described assume no.)
9: Was the intervention described in detail?
10: Was contamination avoided?
11: Was co-intervention avoided?
12: Were results reported in terms of statistical significance?
13: Were the analysis methods appropriate?
14: Was clinical importance reported?
15: Were drop-outs reported?
16: Were conclusions appropriate given the study methods?
na: not applicable: *reliability/validity of whole test battery is described; CC: case control; CS: cross-sectional; BA: before and after; RV: reliability and validity; C: cohort; SC: single case study; RCT: randomized control trial.

Table II. Characteristics of different tests and test populations for upper- and lower-body anaerobic exercise capacity

Device	Test	Spec.	Study, ref.	Impairment	Athletes	Time since impairment	Measurement device; setting
Upper body							
ACE	mWAnT	5 s	21	SCI (C5–C7)	Yes	Unknown	Modified leg cycle ergometer (Ergomedic 620, Monark, Vansbro, Sweden)
		10 s	22	SCI, poliomyelitis, amputation, lower-limb amelia, spina bifida, femur agenesis	Yes	Unknown	Electrically braked ergometer (Lode, Groningen, The Netherlands)
		30 s	17	SCI (paraplegia), amputations (transtibial, transfemoral), polio	Yes/No	Unknown	Arm crank ergometer (Fleish Metabo, Geneva, Switzerland)
			23	Unknown	Yes	4.2 (2.4) years/2.5 (1.9) years	Wheelchair ergometer (Ergomedic 891E, Monark)
			24	SCI, polio, amputation	Yes	Unknown	Arm crank ergometer (MET-300, Cybex, Massachusette, USA)
			25	SCI (paraplegia), amputations, polio	Yes	Unknown	Arm crank ergometer (Fleish Metabo)
			26	SCI (T6–T10)	No	Unknown	Modified leg cycle ergometer (834E, Monark)
			27	SCI (C5–C7)	No	C5 8.2 (3.9), C6 10.0 (7.2), C7 10.6 (7.4) years	Modified leg cycle ergometer (834E, Monark)
			28	SCI (C5–C7)	No	>1 years	Modified leg cycle ergometer (834E, Monark)
			29	SCI (T2–T12)	No	8.1 (7.1) years	Modified leg cycle ergometer (834E, Monark)
			30	SCI (C5–C8)	No	>1 years	Modified leg cycle ergometer (834E, Monark)
			31	SCI (C5–C7)	No	>1 years	Arm crank ergometer (Angio, Lode)
			32	SCI (T5–T12)	No	13.1 (6.6) years	Table-mounted ergometer 834E (Monark)
			33	SCI, polio, amputation	Yes	Unknown	Arm crank ergometer (Monark 891E)
	MW-HIE	–	22	SCI, poliomyelitis, lower-limb amputation, lower-limb amelia, spina bifida, femur agenesis	Yes	Unknown	Isopower arm crank ergometer (Ergometrics 800, Ergoline, Bitz, Germany)
	FV- relationship	–	34	Able-bodied, lower-limb amputation, SCI (thoracic), paraplegias (Heine-Medin disease), CP, developmental defect of lower limbs	Yes/No	Unknown	Modified leg cycle ergometer (838E, Monark)
WCE	mWAnT	8 s	35	Able-bodied	No	na	Standard wheelchair (Quickie EX, Nieuwegein, The Netherlands); friction braked ergometer (VP100H , HEF Tecmachiene, Andrézieux-Bouthéon, France)
		20 s	36	Able-bodied	No	na	Wheelchair ergometer (Niesing et al. (92)); individually adjusted
		30 s	37	SCI (C6–T12), polio	Yes	4–8 years (SCI), 29 years (polio)	Own wheelchair; clamped onto a set of rollers
			12	SCI (C4–L5)	No	C4–C8 14.6 (8.8), T1–T5 15.3 (8.5), T6–T10 10.8 (8.4), T11–L5 7.3 (6.2) years	Wheelchair ergometer (Niesing et al. (92))
			38	SCI (C6–L3/4)	No	141 (66) days	Wheelchair ergometer (Niesing et al. (92))
			39	SCI (C6–L3/4)	No	331 (142) days	Wheelchair ergometer (Niesing et al. (92))
			40	SCI (C4–L4)	No	Unknown	Wheelchair ergometer (Niesing et al. (92))
			41	SCI (T4–L1), amputation (transfemoral), spina bifida, polio	Yes	Unknown	Computerized wheelchair ergometer (Bromakin UK, Loughborough, United Kingdom); own basketball sports wheelchair
			42	SCI (T5–L3), polio	Yes	Unknown	Computer motor-driven wheelchair ergometer (Sopur Ergotronic 9000); own sport wheelchair
			43	Polio, MS, SCI, transtibial amputation	Yes	Unknown	Motor-driven roller device (WILLY, health reliability, Israel); own sport wheelchairs
			44	SCI (C4/5–L5)	No	11.1 (8.2) years	Stationary wheelchair ergometer; own daily wheelchair
			45	SCI (paraplegia, tetraplegia)	Yes/No	8.7 (8.7) and 6.0 (6.5) years	Wheelchair ergometer (Niesing et al. (92))
			46	SCI (paraplegia)	Yes	Unknown	Friction braked wheelchair ergometer; own wheelchair sat
			47	SCI (paraplegia)	Yes	Unknown	Wheelchair ergometer (Niesing et al. (92))
			48	Spina bifida, CP, SCI (T3–L4), polio, amputation	Yes	16.7 (9.89) years	Computerized roller wheelchair ergometer
			49	Able-bodied	No	na	Computer-controlled stationary wheelchair ergometer
			50	Able-bodied	No	na	Wheelchair ergometer (Niesing et al. (92))
			51	Able-bodied	No	na	Wheelchair ergometer (Niesing et al. (92)); standardized settings
			52	Poliomyelitis, spina bifida, hemiplegia, knee arthrosis, SCI (C6–S1), above-knee amputation uni- and bi-lateral	Yes	Unknown	Wheelchair ergometer (Niesing et al. (92)); standardized settings
			53	SCI (C5–S1), poliomyelitis, spina bifida, knee arthrosis, hemiplegia, above-knee amputations uni- and bi-lateral	Yes	Unknown	Wheelchair ergometer (Niesing et al. (92))
			54	Able-bodied and SCI (T8 and lower)	No	na, unknown	Wheelchair ergometer (Niesing et al. (92))
			55	SCI (C5–C7)	Yes	10 (4) years	Wheelchair ergometer (Bromakin); own wheelchair

Table II. *Cont*

Device	Test	Spec.	Study, ref.	Impairment	Athletes	Time since impairment	Measurement device; setting
	Sprint test	5 s	56	SCI (paraplegia), spina bifida, short femur, hip deviations, spastic legs	Yes	Unknown	Wheelchair ergometer (Niesing et al. (92))
		10 s	46	SCI (paraplegia)	Yes	Unknown	Friction braked wheelchair ergometer; own wheelchair sat
			57	SCI (incomplete, L1)	Yes	Unknown	Stationary roller wheelchair ergometer (Bromakin); own wheelchair
		20 s	58	Able-bodied	No	na	Basketball wheelchair (Quickie GPV)
Wheelchair overground	Sprint test	30 s	48	Spina bifida, CP, SCI (T3–L4), polio, amputation	Yes	16.7 (9.89) years	Unknown
		5 m	59	SCI, spina bifida, CP, phocomelia, poliomyelitis	Yes	13.1 (9.4) years	Own sports wheelchair
			60	SCI, knee injury, amputation, spina bifida, hypoplastic right heart syndrome, poliomyelitis, rheumatoid arthritis, shattered calcaneus, complex regional pain syndrome	Yes	Unknown	Unknown
		15 m	50	Able-bodied	No	na	Daily wheelchair (Sopur Starlight 622, Sunrise Medical, Nieuwegein, The Netherlands)
			61*	SCI (paraplegia and tetraplegia)	No	11.8 (11.4) years	Own wheelchair or a laboratory chair fitted to the anthropometrics
			62	SCI (paraplegia and tetraplegia)	No	>10 years	Own wheelchair with instrumented wheel
		20 m	48	Spina bifida, CP, SCI (T3–L4), polio, amputation	Yes	16.7 (9.89) years	Unknown
			63	SCI (T9–L4), motor neuropathy, spina bifida, brittle bones, amputations, myalgic encephalomyelitis, club foot	Yes	Unknown	Adjustable sport wheelchair (Top End Transformer); sports hall with wooden spring flooring
			64	SCI (lower than T9), amputations	Yes	Unknown	Adjustable sport wheelchair (Top End Transformer); sports hall with wooden spring flooring
			65	SCI, amputation, polio, dermoid cyst, Legg–Calvé–Perthes, dysplasia, spina bifida, cauda equina syndrome	Yes	Unknown	Synthetic indoor court
			66	SCI, CP, osteogenesis imperfect, distal-limb weakness, vanishing white matter disease	Yes	Unknown	Wireless time gates (Brower, UT, Draper, USA)
		75 m	67	Able-bodied and SCI (nr)	No	20 (9.9) years	Able-bodied; standard non-adjustable multisport MW (Invacare Küschall); SCI used their own personalized multisport MW
		100 m	46	SCI (paraplegia)	Yes	Unknown	Friction braked wheelchair ergometer; own wheelchair sat
Wheelchair treadmill	Sprint test	15 m	68*	SCI (paraplegia, tetraplegia)	No	Unknown	Wheelchair (Sopur Starlight)
Lower body							
Bicycle ergometer	mWAnT	30 s	69	CP	No	Unknown, age range 18–65	Excalibur bicycle ergometer (Lode)
			70	Able-bodied, CP	Yes/No	na, age 18–49 years	Excalibur bicycle ergometer (Lode)
			71	Able-bodied, CP	Yes/No	Unknown	Velotron Dynafit Pro (Racermate Inc., .: Seattle, USA)
Recumbent ergometer	mWAnT	9 s	72	CVA (hemiplegia)	No	83.2 (53.0) days	StrengthErgo (Mitsubishi Electric Engineering Company, Tokyo, Japan); standardized settings
No device	Sprint test	10 m	73	Amputation (unilateral, transtibial)	Yes	Unknown	Light gates (Tumer Electronic, Turkey); crutches without prostheses
		20 m	73	Amputation (unilateral, transtibial)	Yes	Unknown	Light gates (Tumer Electronic); crutches without prostheses
		25 m	74	CVA	No	2.5 years	–
		30 m	73	Amputation (unilateral, transtibial)	Yes	Unknown	Light gates (Tumer Electronic); crutches without prostheses
	Jump test	Counter movement	73	Amputation (unilateral, transtibial)	Yes	Unknown	Force plate (Tumer Electronic); crutches without prostheses
			75	Amputation (unilateral, transtibial)	Yes/No	Athletes: 12.2 (7.2) years Non-athletes: 13.7 (7.7) years	–
		Squad	73	Amputation (unilateral, transtibial)	Yes	Unknown	Force plate (Tumer Electronic); crutches without prostheses

*Test is part of a larger test battery, test result not individually analysed.
ACE: arm crank ergometer; WCE: wheelchair ergometer; mWAnT: modified Wingate protocol; MW-HIE: Mechanical Work in a High Intensity Exhaustion Exercise Test; FV-relationship: force velocity relationship; SCI: spinal cord injury; na: not applicable.

Table III. Protocols used in the different tests for upper- and lower-body anaerobic capacity

Device	Test	Study, ref	Duration/distance	Efforts	Warming up	Resistance	Outcome parameters	Rest between efforts	Initial conditions
Upper body									
ACE	mWAnT	17	30 s	1	nr	35 g/kg	Ppeak (W); Pmean (W); Fatigue index	na	nr
		21	5 s	3	5 min (30 W, 60 rpm); Intervals 30 s rest/30 s (35 W, 70 rpm)	2.0, 3.0, 4.0% BM	Ppeak (W)	5 min (0W)	0 m/s
		22	10 s	1	nr	3.1–7.1% BW	Pmean (W)	na	nr
		23	30 s	1	nr	50 g/kg	Ppeak (W); Pmean (W); Fatigue index; Peaktime (s); Lowtime (s)	na	nr
		24	30 s	1	10 min; 3×5 s all-out sprint, 5 min rest	nr	Ppeak (W); Pmean (W); Fatigue index	na	Vmax
		25	30 s	1	nr	25 g/kg	Ppeak (W); Pmean (W); Fatigue index	na	nr
		26	30 s	1	3 min (0 W)	3.5% BM	Ppeak (W); Pmean (W)	na	Vmax
		27	30 s	2	3–5 min (0 W)	1 (C5), 2 (C6), 3 (C7) % BM	Ppeak (W); Pmean (W)	2–4 days	Vmax
		28	30 s	6	3–5 min (0 W)	1, 1.5, 2, 2.5, 3, 3.5% BM	Ppeak (W); Pmean (W)	20 min	Vmax
		29	30 s	2	3–5 min (0 W)	3.5% BM	Ppeak (W); Pmean (W); Fatigue index	2–7 days	>100 rpm
		30	30 s	1	nr	3.5% BM	Ppeak (W); Pmean (W); time to Ppeak (s)	na	nr
		31	30 s	1	2 min (60 rpm, 0 W)	1–2% BM	Ppeak (W); Pmean (W); Pmin (W); Fatigue index	na	>25 rpm
		32	30 s	2	nr	3.5% BM	Ppeak (W); Pmean (W)	30 min	nr
		33	30 s	1	nr	nr	Ppeak (W/kg); Pmean (W/kg); Pmin (W/kg); Fatigue index, peak time (s); low time (s)	na	nr
	MW-HIE	22	Until 70 rpm cannot be maintained	1	nr	130% of mechanical aerobic peak power	Mechanical Work (J)	na	nr
	F-V relationship	34	Until 100 rpm cannot be maintained	5–7	Standard warm-up	Individually based	Ppeak; F0; V0	5 min	Rolling start
WCE	mWAnT	72	30 s	1	nr	nr	Ppeak (W)	na	75% Vmax
		12	30 s	1	nr	0.25, 0.50, 0.75 N/kg	Ppeak (W); Pmean (W)	na	nr
		35	8 s	9	5 min (1 and 2.5 Nm)	0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4 Nm	Ppeak (W); Pmean (W)	5 min	0 m/s
		36	20 s	9	nr	0.8–22 Nm/wheel	Vmean (m/s); Torque (Nm); Pmean (W)	20 min	0 m/s
		38	30 s	1	3 min (0 W)	Formula Janssen et al. (44)	Ppeak (W); Pmean (W); Torque (Nm); Linear velocity (m/s)	na	nr
		39	30 s	1	3 min (0 W)	Formula Janssen et al. (44)	Ppeak (W); Pmean (W); Torque (Nm); Linear velocity (m/s)	na	nr
		40	30 s	1	3 min (0 W)	0.25, 0.50, 0.75 N/kg	Ppeak (W); Pmean (W)	na	Rolling start
		41	30 s	1	nr	No resistance	Ppeak (W)	na	1.5 m/s
		42	30 s	1	nr	1.88–4.3 Nm	Ppeak (W); Pmean (W); Vmax (km/h); Vmean (km/h)	na	Vmax
		43	30 s	1	Intervals 30 s work/30 s rest; 5 s sprint (2–3×); 5 min rest	19.6 N	Ppeak (W); Pmean (W); Fatigue index; Velocity (m/s)	na	Vmax
		44	30 s	1	Near maximum speed, brief period	0.25, 0.50, 0.75 N/kg	Ppeak (W); Pmean (W)	na	nr
		45	30 s	1	nr	Normalized to BM	Pmean (W)	na	nr
		46	30 s	6	nr	1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4 kg	Ppeak (W); Pmean (W)	20 min	60% Vmax
		47	30 s	2	nr	0.75 or 1 N/kg	Ppeak (W); Pmean (W)	nr	0 m/s
		48	30 s	1	nr	10 N/wheel	Pmean (W)	na	Vmax
		49	30 s	1	3 min; 20% estimated PO	Formula Janssen et al. (44)	Ppeak (W); Pmean (W)	na	0 m/s
		50	30 s	1	4–8 strokes forcefully; 2 min rest	Formula Janssen et al. (44)	Ppeak (W); Pmean (W)	na	0 m/s

Table III. Cont

Device	Test	Study, ref	Duration/distance	Efforts	Warming up	Resistance	Outcome parameters	Rest between efforts	Initial conditions
		51	30 s	1	3 min; 20% estimated PO	Formula Janssen et al., 1993 (44)	Ppeak (W); Pmean (W)	na	0 m/s
		52	30 s	2	5 min (0 W)	2.5, 5, 7.5, 10% BM; based on test trial	Ppeak (W); Vmax (m/s)	10–15 min	0 m/s
		53	30 s	2	5 min (0 W)	2.5, 5, 7.5, 10% BM; based on test trial	Ppeak (W); Pmean (W); Vmax (m/s); Vmean (m/s)	10–15 min	0 m/s
		54	30 s	2	nr	0.5, 0.75, 1.0 N/kg	Ppeak (W); Pmean (W)	nr	nr
		55	30 s	1	5 min (0 W); 2×3 s max	nr	Ppeak (W); Pmean (W); Time to Ppeak (s); Fatigue index	na	1 m/s
	Sprint test	56	5 s	6	1 min (1 m/s; 0.15 W/kg)	No resistance	Vmax (km/h), acceleration (m/s^2), Ppeak (W)	nr	Rolling start
		46	10 s	6	nr	No resistance	Vmax (m/s)	20 min	0 m/s
		57	10 s	10	nr	No resistance	Vmax (m/s); Fatigue index	30 s	1 m/s
		58	20 s	6	5 min (0 W)	No resistance	Vmax (m/s)	HR <100 bpm	0 m/s
Wheelchair overground	Sprint test	46	100 m	2	1,600 m; 5 min static flexibility	No resistance	Performance time (s)	3 min	0 m/s
		48	30 s	1	nr	No resistance	Covered distance (m)	2 min	0 m/s
		48	20 m	1	nr	No resistance	Performance time (s)	na	0 m/s
		50	15 m	1	5–10 min	No resistance	Performance time (s)	na	0 m/s
		59	5 m	3	Regular warming-up	No resistance	Performance time (s)	2 min	0 m/s
		60	5 m	3	nr	No resistance	Performance time (s)	nr	0 m/s
		61	15 m	1	nr	No resistance	Performance time (s)	2 min	0 m/s
		62	15 m	1	5–10 min	No resistance	Performance time (s)	na	0 m/s
		63	20 m	3	nr	No resistance	Performance time (s)	2 min	0 m/s
		64	20 m	3	nr	No resistance	Performance time (s)	2 min	0 m/s
		65	20 m	3	5 min low intensity, stretching, 2 accelerations	No resistance	Performance time (s)	2 min	0 m/s
		66	20 m	3	20 min standardized warming-up	No resistance	Performance time (s)	30s	0 m/s
		67	75 m	4	nr	No resistance	Performance time (s)	As long as necessary	0 m/s
Wheelchair treadmill	Sprint test	68	15 m	1	nr	No resistance	Performance time (s)	na	0 m/s
Lower body									
Bicycle ergometer	mWAnT	69	30 s	1	5 min (60 rpm, PO = 100 W)	Maximum 7.1% BM	Ppeak (W); Pmean (W)	na	nr
		70	30 s	1	5 min (60 rpm, PO = 100 W)	Maximum 7.1% BM	Ppeak (W); Pmean (W)	na	nr
		71	30 s	1	5 min (PO = 1.5 W/kg)	7.5% BM	Ppeak (W/kg); Pmean (W/kg)	na	100 rpm
Recumbent ergometer	mWAnT	72	9 s	1	3 min (10 W)	15% leg extension peak torque	Pmean (W)	na	nr
No device	Sprint test	73	10 m	2	nr	No resistance	Performance time (s)	1 min	0 m/s
		73	20 m	2	nr	No resistance	Performance time (s)	1 min	0 m/s
		73	30 m	2	nr	No resistance	Performance time (s)	1 min	0 m/s
		74	25 m	1	1.5 min	No resistance	Performance time (s)	na	0 m/s
	Jumptest	73	Squad	3	nr	No resistance	Jump height (cm)	2 min	Knees flexed
		73	Counter Movement	3	nr	No resistance	Jump height (cm)	2 min	Upright position
		75	Counter Movement	3	nr	No resistance	Jump height (cm)	nr	Upright position

ACE: arm crank ergometer; WCE: wheelchair ergometer; mWAnT: Modified Wingate protocol; MW-HIE: Mechanical Work in a High Intensity Exhaustion Exercise Test; F-V relationship: force-velocity relationship; na: not applicable; nr: not reported; BM: body mass (kg); BW: body weight (N). Ppeak: peak power; Pmean: mean power; rpm: rotations per minute; Vmax: maximum velocity; Pmin: minimum power; Vmean: mean velocity

Anaerobic capacity was measured in both upper [56 protocols] (12, 17, 21–68) and lower body [11 protocols] (69–75) for different diagnostic groups (Fig. 2). Five different anaerobic tests were distinguished for upper body, while 3 different anaerobic tests were found for lower-body assessment. Two types of tests, modified WAnT (mWAnT) and sprint test, were found for anaerobic assessment of both the upper and lower body, while a diversity of protocols was seen within these tests.

In line with the heterogeneity of protocols, different definitions for WAnTs were found. In this review, a mWAnT was defined as an anaerobic exercise test performed on an ergometer, in which power out (PO) was the main outcome. However, 15 studies designated as being a mWAnT in this review, were termed a sprint tests in the original article itself (12, 21, 35, 36, 38, 39, 41, 45, 46, 49, 51–54).

Upper-body anaerobic tests

Protocols for upper-body anaerobic assessment were found using 2 different device types, arm crank ergometry (ACE) [16 protocols] (17, 21–34) and wheelchair exercise tests [40 protocols] (12, 35–68) (Table II) in which wheelchair testing was performed either on an ergometer (WCE) [26 protocols] (12, 35–58), overground [13 protocols] (46, 48, 50, 59–67) or on a treadmill [1 protocol] (68) (Table III).

ACE mWAnT. Fourteen studies performing a mWAnT on an ACE were found in athletes and non-athletes with different physical disabilities (17, 21–33). mWAnT protocols lasted 5 s [1 protocol] (21), 10 s [1 protocol] (22) and 30 s [11 protocols] (17, 23–33). Two protocols did not report resistance (24, 33), where others scaled resistance to body mass [12 protocols] (17, 21–23, 25–32), ranging from 1% in cervical SCI non-athletes up to 7.1% body mass in wheelchair athletes. One protocol in tetraplegic patients used no initial velocity (21), where initial velocity was set at maximum speed in 4 studies (24, 26–28). Two tests in paraplegic and tetraplegic patients, started when 25 or 100 revolutions per minute (rpm) was reached (29, 31). The 30 s mWAnT was assumed to be reliable in patients with cervical SCI (28).

ACE Mechanical Work in a High Intensity Exhaustion Exercise test (MW-HIE). One study used a MW-HIE test on an ACE for measuring anaerobic capacity in physically disabled athletes (22). During the test, participants had to propel at least 70 rpm against a high resistance for as long as possible. Resistance was set at 130% of peak aerobic power output (POpeak), measured by a previously performed aerobic test. Anaerobic work (J) was calculated by multiplying the resistance and duration of the test.

ACE Force-velocity (FV) relationship test. A FV-relationship test was found for evaluating anaerobic power in disabled weight lifters and able-bodied young adults (34). During this test, maximal resistance against which the participant can propel an ACE for 6 s with a velocity of at least 100 rpm is determined. From this test, POpeak is calculated and maximal rotation speed and maximal resistance are predicted.

Wheelchair mWAnT. In upper-body wheelchair testing, mWAnT and sprint test protocols were found (Fig. 2). Wheelchair mWAnT protocols were applied in able-bodied subjects [6 protocols] (35, 36, 49–51, 54), physically disabled athletes with different physical disabilities [11 protocols] (37, 41–43, 45–48, 52, 53, 55), and SCI non-athletes [7 protocols] (12, 38–40, 44, 45, 54). Subjects were tested in both the clinical rehabilitation and chronic phase. Protocols lasting 8 and 20 s were used in able-bodied subjects (35, 36), where 30 s mWAnTs were used for able-bodied subjects and patients with different physical disabilities (12, 37–55) (Table II).

Large variation in applied resistance settings was found among different protocols (Table III). In most protocols resistance was scaled to body mass where different scaling factors were used for different physical disabilities [8 protocols] (12, 40, 44, 45, 47, 52–54). Resistance ranged from 0.25 N/kg in high cervical SCI non-athletes to 1.0 N/kg in thoracic SCI patients. In 1 protocol, no resistance was applied, in order to better simulate game situations (41). Five protocols (38, 39, 49–51) based resistance on an estimation of the expected mean anaerobic power by performing an isometric strength test, using equation 1 (44):

$$P30\ (W/kg) = 0.51 * Fiso\ (N/kg) - 0.18 \quad \textit{(equation 1)}$$

in which P30 is the estimated mean anaerobic relative power and Fiso is isometric wheelchair push strength relative to the total weight (wheelchair + subject) (44).

One study determined resistance on a simulation, in which resistance, while participants sat passively on the ergometer, was multiplied by a factor of 0.3 to simulate propelling on a tarmac road (42). Lastly, 6 protocols used a fixed resistance (35, 36, 42, 43, 46, 48) varying between 0.8–22 Nm/wheel, 10 N/wheel, 19.6 N, 0–4.3 Nm, and 1–2.4 kg (Table III).

Eight protocols used a rolling start (37, 40–43, 46, 48, 55), while subjects in 8 studies started from zero velocity (35, 36, 47, 49–53). In 5 protocols initial velocity was scaled to patient's maximum speed on the WCE (60–100%) (37, 42, 43, 46, 48). Two protocols fixed initial velocity at 1 and 1.5 m/s (41, 55), while one protocol did not report precise initial velocity (40). Moreover, 2 different WCE types were used (Table II). A computerised stationary wheelchair ergometer,

in which ergometer settings were standardized for all participants, was used in 15 protocols (12, 35, 36, 38–40, 45, 47–54). Other protocols used an ergometer on which participants performed the test using their own wheelchair (37, 41–44, 46, 55).

Wheelchair sprint test. Sprint tests, in which participants propel themselves as far as possible within a fixed time, were found in 5 studies (46, 48, 56–58). Three protocols were performed on a WCE (46, 56–58), whereas 1 protocol was over ground (48) (Table II). Covered distance or maximal velocity was measured during 5, 10, 20, or 30 s. A 10 s protocol was performed by paraplegic SCI patients (46, 57), whereas a 20 s protocol was found in able-bodied wheelchair users (58). The 5 s and the 30 s protocol were performed in wheelchair athletes with different physical disabilities (48, 56).

Furthermore, sprint tests over a set distance, in which performance time was measured, were found [13 protocols] (46, 48, 50, 59–68). Sprint tests were performed by able-bodied persons using a wheelchair [2 protocols] (50, 67) or physically disabled (non)athletes with different physical disabilities [12 protocols] (46, 48, 59–68). In all studies that mentioned time since impairment, sprint tests were performed during the chronic phase. Covered fixed distances ranged from 5 m in physically disabled athletes (59, 60) to 100 m in athletes with SCI paraplegic (46). One of the 4 studies using a 15 m sprint test was performed on a treadmill (68), other protocols were performed over ground. The 100 m sprint test was performed outdoors on an athletics track, where other protocols were indoors.

The 5 m over-ground sprint test showed a good reliability; however, the validity was questionable (60). The 15 m over ground sprint test had a poor validity for measuring anaerobic capacity in able-bodied adults, compared with a mWAnT. Also, the maximal velocity during the test was no good indicator for anaerobic capacity. However, PO, measured from the 5th to the 15th m of the 15 m sprint (P5–15 m), was found to be moderately valid (50). The 20 m sprint test and the 30 s sprint test are highly correlated (48). Since the 30 s sprint test is valid, the 20 m sprint test is suggested to be suitable for measuring anaerobic capacity in wheelchair athletes (48). Lastly, the 100 m sprint test in athletes with SCI correlated highly with a 30 s WAnT on a WCE (46).

Lower-body anaerobic tests

Eleven protocols assessing anaerobic capacity in lower-body exercise were found (69–75). Three different tests can be identified; mWAnT, sprint tests and jump tests (Table II) using a variety of protocols (Table III).

mWAnT. Four different lower-body mWAnT protocols were found using a bicycle [3 protocols] (69–71) or recumbent cycle ergometer [1 protocol] (72). Three 30 s bicycle protocols were found in patients with CP and able-bodied wheelchair users (69–71), a 9 s recumbent test was performed in patients with CVA (72). Resistance in the 3 bicycle ergometer protocols was scaled to body mass (69–71), where resistance was set at 15% of the leg extension peak torque in the recumbent ergometer mWAnT. Initial velocity was reported in one study, and set at 100 rpm (71). Reliability and validity of a 9 s protocol using a recumbent ergometer is ascertained in patients with CVA (72) (Tables II and III).

Sprint tests. Sprint tests in which a set distance had to be walked/ran while performance time was measured, were found [4 protocols] (73, 74). Distances covered during these tests were 10, 20, 25 or 30 m. Only the 25 m test was performed by patients with CVA (74), whereas all other sprint tests were performed in 1 study on amputee soccer players (73). During these tests, participants used crutches, without using prostheses.

Jump tests. In 2 studies anaerobic capacity was measured using the counter-movement and squad jump. These tests were performed by unilateral lower-limb amputee soccer players, without using crutches or prostheses. Each jump was repeated 3 times, of which the highest jump was reported (73, 75). Using vertical jump height (VJD, cm) and body mass (BM, kg), total work produced by the body (P) was calculated using the equation of Genuario & Dolgener (76), as follows:

$$P = 2.21 * BM * (\sqrt{VJD})$$

DISCUSSION

The aim of this study was to systematically review tests and protocols used for the measurement of anaerobic capacity in people with different physical physical disabilities in the context of rehabilitation. A further aim was to provide direction for clinical use and further research. A total of 57 papers were included. There is considerable diversity among tests as well as among protocols, partly associated with the diversity of the populations studied (Tables II and III). In general, mWAnT [40 protocols] and sprint tests [21 protocols] were used most often, using a variety of protocols (Table III). All tests found in this literature review indirectly measured anaerobic capacity, by measuring work in a situation in which the contribution of the aerobic system is assumed to be low. No direct measures of anaerobic capacity were found using muscle biopsies. Thus, all tests in this review estimate anaerobic capacity indirectly, which limits

their validity. In clinical practice, muscle biopsies are less feasible compared with the field tests found in this review. The authors suggest that this explains why no direct measurements are found.

In this literature review an important and self-evident distinction is made between upper- and lower-body anaerobic testing. In able-bodied subjects, physiological responses between upper- and lower-body exercise testing differed considerably (77, 78). Most tests used in upper-body anaerobic exercise testing were mWAnTs. All mWAnTs found were modified from the original protocol (16) in terms of duration, device, resistance or initial velocity, for use in the specific study population.

Within upper-body mWAnT testing, a distinction can be made between using a WCE and ACE. In patients with SCI aerobic capacity was higher when using an ACE compared with a WCE (79, 80). This can be explained by the lower mechanical efficiency of wheelchair driving compared with arm crank ergometry (81). Anaerobic capacity measured by a 30 s mWAnT protocol on a WCE was strongly influenced by propulsion technique (52). Therefore, it is questionable whether this test strictly measures anaerobic capacity. The authors suggest ACE testing to be less technique-dependent because of the continuity of the movement. In ACE testing original ACEs and modified leg ergometers were used. Modified leg ergometers lead to higher physiological responses, compared with original ACEs (82).

Moreover, 14 wheelchair sprint tests over a set distance or time were found. For upper-body anaerobic testing, the validity of the overground wheelchair 15 m sprint test was proved to be insufficient. However, measuring PO by using an instrumented wheel was found to be moderately valid (50). The lower resistance during over-ground sprinting leads to velocities higher than 3 m/s, which induces coordination problems (50). The MW-HIE test, which is a ACE mWAnT protocol with no fixed duration, was found to elicit a blood lactate production significantly higher than did a 30 s WAnT, whereby it was suggested to be more reliable in assessing lactic anaerobic capacity compared with the WAnT (22).

In lower-body anaerobic exercise testing mWAnTs using a bicycle [3 protocols] and recumbent ergometer [1 protocol] were found. Bicycle and recumbent ergometers are suggested to differ in efficiency. Within bicycle ergometers, a distinction can be made between mechanically and air-braked ergometers. Air-braked ergometers lead to substantially higher anaerobic power and capacity compared with mechanically braked ergometers (83). The lack of conformity in device use can bias results concerning anaerobic capacity testing, which reduces the applicability of comparative interpretations (Table II). Moreover, lower-body sprint tests were found. In lower-limb amputees, no relationship was found between walking ability and anaerobic capacity, measured with a sprint test (8). Therefore it is questionable whether sprint tests are reliable for measuring anaerobic capacity. Lastly, jump tests [3 protocols] were found for lower-body anaerobic exercise testing, and proved feasible only for a limited part of the rehabilitation population. Vertical jump height is moderately correlated to anaerobic capacity, as measured using the original WAnT (16).

The anaerobic system includes both the creatine phosphate system and the glycolysis system. During short intervals (up to 10 s), the creatine phosphate system is primarily strained (84). During intervals longer than 30–45 s energy is primarily generated by the aerobic system (9, 10). In this review protocols that were shorter than 10 s or longer than 30 s were found. The main reason for shortening the protocol was the decreased physical capacity of patients (72). The FV-relationship test, performed on an ACE, consisted of 5–7 efforts each lasting 6–8 s. Moreover, mWAnT protocols lasting 5 or 8 s were found. Thus, it is arguable whether these tests measure the entire anaerobic capacity. The mean duration of the MW-HIE test was 70 s. For this test it is therefore arguable whether the dominant energy supply is of anaerobic nature and whether it is therefore useful for measuring anaerobic capacity. The duration of the exercise influences mean power during a short all-out test to predict anaerobic capacity (85). Test duration is thereby expected to influence the validity of the protocol.

During sprinting, all 3 energy systems contribute to the energy supply, even during exercises of 6 s duration (84). Thereby it is impossible to exclusively test anaerobic capacity, since there would have been an aerobic contribution in all tests. The magnitude of this aerobic contribution can be measured by breath-by-breath analysis. During a 30 s mWAnT protocol on a WCE, 29.8% of the total energy production was aerobic in patients with SCI and those with polio. During a 30 s ACE mWAnT in able-bodied athletes, an 18% aerobic contribution was found. The aerobic contribution in WCE and ACE mWAnT is comparable with that in the original WAnT (42).

The applied resistance is assumed to have a significant effect on POpeak and mean power output (POmean) in WCE testing. When resistance decreases, PO also decreases. In order to avoid influences of coordination, resistance had to be set so that the maximum speed did not exceed 3 m/s (36). In the reviewed studies, the applied resistance in ACE mWAnT was lower compared with the resistance found in WCE mWAnT testing. This seems contradictory, since mechanical efficiency is higher for ACE than for WCE (81). In

upper-body anaerobic testing, optimal resistance setting in able-bodied subjects varies between different ergometers and should be relative to body mass (16). The strong relationship between isometric strength and anaerobic capacity in SCI, indicates that it appears effective to base resistance on a prediction of anaerobic capacity (44). For other diagnoses, investigating this relationship would be of interest in future research.

The applied resistance in lower-body mWAnT testing, as found in this study, was lower compared with the resistance as advised in able-bodied WAnT testing (16). Despite the developers suggesting fat-free mass or muscle mass to be a better alternative, in the original bicycle WAnT, resistance is scaled to body mass, or a combination of body mass and leg volume. Because of increased weight due to a more sedentary lifestyle in physically disabled individuals, it can be difficult to set optimal resistance using only body mass (51).

To exclude the acceleration phase, the original WAnT was developed using a rolling start. However, for reasons of low taxability in physically disabled people, and to avoid coordinative problems, it can be suggested not to use a rolling start. The pattern of anaerobic power output differs between different pacing strategies at supramaximal intensity, while pacing strategy does not influence total anaerobic work during a race (86). Because of the effect of pacing on anaerobic power output, the decision whether to use a rolling start can influence the validity of the test protocol.

Most studies found were on upper-body exercise and wheelchair-bound patients with SCI. However, in 2010 only 10% of the 650 million people who live with some form of disability require a wheelchair. The prevalence of SCI varied between 0.02% and 0.13% worldwide (87). It is remarkable that SCI is studied extensively compared with other populations with a higher incidence, which are also included in the current review. Moreover, a considerable number of studies were on able-bodied wheelchair users. Despite the physiological and biomechanical differences between wheelchair-dependent and able-bodied subjects during wheelchair propulsion (88), in this review it was decided to also include studies on able-bodied wheelchair users, since the main focus was on tests and protocols used instead of outcomes. In some of the diagnoses under study, muscle strength or coordination is physically disabled (8, 11, 51, 88–91). When strength and/or coordination is physically disabled to a high extent, this can impede test performance, and will be, instead of the anaerobic capacity, the limiting factor during the test.

All protocols found in this review can be assumed feasible for the specific population tested in the different studies. Ergometers used for fitness testing are usually expensive, non-portable devices. This may restrict the feasibility of these tests in different environments (17). The measurement of PO with an instrumented wheel can be an alternative in overground wheelchair sprint testing, and is thought to be feasible, since instrumented wheels are portable, implemented in the subject's own wheelchair, and are less expensive compared with ergometers (50).

The quality of this review may have been influenced by reporting and interpretation bias. It is possible that articles of interest were not found by the search strategy used. However, with the detailed search terms used, and the independent screening performed by 2 assessors, the risk of selection bias was limited.

In clinical practice we suggest measuring anaerobic capacity using a 30 s mWAnT protocol, since this test is a modification of the valid and reliable WAnT (16), and both anaerobic energy systems are strained during the testing period. Moreover, this test can be easily adapted by adapting device, resistance and initial velocity. When measuring individual anaerobic capacity, a device that is used in daily life is suggested, because of the generalizability to capacity in daily life. Resistance and initial velocity should be based on the capacity of the patient. However, it is necessary to study reliability and validity of the protocols on the specific population first.

Sprint tests could be an alternative when the equipment necessary for the mWAnT is not available. No benefits of time-fixed or distance-fixed sprint tests were found compared with each other. Nevertheless, the duration or distance of a sprint test has to be set so that the energy supply is of anaerobic nature, in which both the creatine phosphate and the glycolysis systems will be strained. Therefore, tests lasting 20–45 s are advised. Also, it has to be ensured that the test will not contain agility factors.

Reliability and validity of the use of mWAnT protocols were tested in several populations. However, reliability and validity in other populations, as well as the optimal setting of resistance and initial velocity, have to be evaluated in future research. Moreover, future research investigating the reliability and validity of sprint tests, eventually by measuring PO by using an instrumented wheel (in case of wheelchair users) in different populations is needed. Furthermore, more research should be performed on the MW-HIE test, since only one study was found using this test, of which results were very promising. The level of anaerobic capacity is highly inhomogeneous between people with different physical disabilities, ages, and activity levels. Therefore, standardization of protocols, which can be individualized by, for instance, applying different resistances, is essential for anaerobic testing in physically disabled individuals and should therefore be of increased attention in future research. For research

purposes, when measuring intra-individual differences, it is recommended to use a device that none or all of the participants is using in their daily lives.

In conclusion, experimental tests and protocols for anaerobic exercise testing in physically disabled people were found to be highly diverse. When selecting a test for measuring individual anaerobic capacity in rehabilitation patients, it first should be considered whether the equipment for a mWAnT is available. When equipment is available a 30 s mWAnT should be performed using the device that is primarily used in daily locomotion. When mWAnT equipment is not available a sprint test lasting 20–45 s is a good alternative. In patients that use a wheelchair for daily locomotion, a wheelchair sprint test is preferred, while a sprint test without any device (walk test) is preferred for patients who do not use a wheelchair for daily locomotion. Future research is needed for standardization of tests in which protocols can be individualized to the specific patient, and for determining the reliability and validity of the specific protocols.

The authors declare no conflicts of interest.

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