Journal of Sports Sciences

ISSN: 0264-0414 (Print) 1466-447X (Online) Journal homepage: www.tandfonline.com/journals/rjsp20

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To cite this article: Janis Fiedler, Maximiliane Thron, Stefan Altmann, Sascha Härtel, Friedrich Barsch, Lars Schlenker, Susanne Krug, Klaus Bös & Alexander Woll (2025) Reference standards for power at the lactate threshold 2 for cycle ergometry throughout the lifespan in Germany, Journal of Sports Sciences, 43:16, 1654-1664, DOI: 10.1080/02640414.2025.2517913

To link to this article: https://doi.org/10.1080/02640414.2025.2517913

JOURNAL OF SPORTS SCIENCES
2025, VOL. 43, NO. 16, 1654–1664
https://doi.org/10.1080/02640414.2025.2517913

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Reference standards for power at the lactate threshold 2 for cycle ergometry throughout the lifespan in Germany

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ABSTRACT

Cardiovascular fitness is an important health marker but reference values for the performance at lactate thresholds are lacking. This study aimed to provide reference standards for the performance on the cycle ergometer at fixed and individual lactate threshold 2 concepts throughout the lifespan. Data from two nationwide studies in Germany (KiGGS wave 2 and DEGS1 study) were pooled to a final sample of 2389 female and 2801 male participants aged 14–64. The data includes the results of an incremental bicycle ergometer test for the parameters absolute (W) and relative (W/kg) power at a fixed (3 mmol/l, LT_{2fix}) and at an individual lactate threshold 2 (base lactate + 1 mmol/l, LT_{2ind}). Generalized additive models for location, scale, and shape (GAMLSS) were used to calculate the reference values. The LT_{2ind} was reached at lower power than the LT_{2fix}. Throughout the lifespan, relative power had its peak at 14 years, declined until age 20 and then declined further but slower until the maximum age of 64 years. Absolute power remained fairly stable until age 45 after which it slowly declined until maximum age. The presented reference values can be used for estimating cardiorespiratory fitness among adolescents and adults in Germany.

KEYWORDS

Cardiorespiratory exercise testing; aerobic endurance; fitness; percentiles

Introduction

Physical performance monitoring can help identify deficits in performance at an early stage in the general population and offer opportunities to improve performance and improve health across the lifespan (Janssen & Leblanc, 2010; Phan et al., 2022). Different established methods are available for the assessment of physical performance and each method has its advantages and disadvantages (Mann et al., 2013). The maximum achievable power, heart rate, oxygen uptake capacity (VO2max), and metabolic equivalents are common markers for performance (Ghosh, 2004; Thompson et al., 2013). However, the evaluation of maximum physical performance parameters can entail a certain risk that increases with participants age, comorbidities, and exercise intensity due to potential load-inducible complaints (e.g., provocation of myocardial infarction) (Myers et al., 2009). Therefore, submaximal parameters like lactate thresholds are of particular importance, as they already provide information about individual cardiovascular fitness under submaximal physical stress (Jamnick et al., 2020; Löllgen & Leyk, 2018) and are especially useful for exercise prescription (Franklin & Cushman, 2011) to counter the physically inactive lifestyle of modern human beings.

Physical inactivity increases the risk of developing cardiometabolic diseases and contributes to all-cause mortality (Lee et al., 2012). In 2019, the prevalence of insufficient physical activity reached 42.3% within the populations of Western industrialized nations (Guthold et al., 2020) and secular trends show that cardiorespiratory fitness declined alarmingly (Leone et al., 2023). During the COVID-19 pandemic, this trend has even intensified (Xiang et al., 2020). This trend is already evident in children and adolescents (Tremblay et al., 2011; Wilhite et al., 2022; Woll et al., 2011) and might therefore be an indicator of an alarming increase in diseases associated with physical inactivity in the future. According to the current World Health Organization (WHO) recommendations, regular aerobic physical activity (at least 60 min moderate to vigorous PA per day on average for children and at least 150 min moderate to vigorous PA per week for adults), combined with strengthening exercises, provides the greatest health benefit for

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/02640414.2025.2517913.

children and adults (Bull et al., 2020). Aerobic exercise leads to adaptive structural and functional tissue responses and can contribute to an improvement of cardiovascular and overall fitness (Fang et al., 2021; Scharhag-Rosenberger et al., 2012; Tanaka & Shindo, 1992). Due to these synergistic effects, an individual's cardiovascular fitness can be considered a relevant marker for assessing a healthy lifestyle. Thus, objectifying a person's cardiovascular fitness could contribute to a better understanding of an individual health and risk profile. For example, people with a high-risk physically inactive lifestyle should be encouraged to perform a greater amount of aerobic physical activity (Bull et al., 2020; Piercy et al., 2018). Here, published data in representative samples play an important role and serve as reference values that can guide decisions for early interventions (Finger et al., 2021; Niessner et al., 2020; Ortega et al., 2023; Vainshelboim et al., 2020).

There are important published reference values for estimated maximum cardiovascular fitness, e.g., from shuttle run and physical working capacity tests (Finger et al., 2021; Niessner et al., 2020; Ortega et al., 2023), and ventilatory threshold norms (in mLo2/kg/min) across the lifespan (Vainshelboim et al., 2020). However, evidence about performance (W) at the lactate threshold 2 is limited to small populations (e.g Hauser et al. (2011)). During the last century, various lactate threshold concepts have been developed and verified (Faude et al., 2009; Wackerhage et al., 2022). These concepts can be consulted for the accessibility of cardiovascular fitness and training control, especially in competitive sports (Billat, 1996; Heuberger et al., 2018). It can be summarized that most of the concepts try to objectify the maximum endurance capacity of a person for long-time performances (Meyer et al., 2005). In this context, the lactate threshold 2 attempts to define the point of physical performance at which aerobic cardiovascular fitness can be sustained for an extended period in an equilibrium of lactate formation and decomposition. This is also called maximal lactate steady state (maxLASS), which is the highest constant-work rate associated with elevated but stable blood lactate levels (Billat et al., 2003; Spurway, 1992; Urhausen et al., 1993; Wasserman, 1986). From a metabolic point of view, this can be understood as the highest equilibrium of energy provision by oxidative phosphorylation (Mader & Heck, 1986). Föhrenbach et al. defined the maxLASS based on results from a cohort study at about 3 mmol/L as a fixed lactate threshold 2 (LT_{2fix}) that does not consider interindividual differences in lactate kinetics (Föhrenbach et al., 1987). To consider such interindividual differences, Dickhuth et al. framed the individual lactate threshold 2 (LT_{2ind}) for cycling and defined it as 1 mmol/L above the minimum lactate equivalent (L. V. Billat, 1996; Dickhuth, Yin, et al., 1999). These lactate thresholds can be used to objectify and monitor the development of cardiovascular fitness during exercise interventions (Tuttor et al., 2018). In addition, lactate thresholds can be used to define the individual aerobic training range more precisely compared to only heartrate-based methods. The heart rate at the threshold can then be used for more targeted training control and monitoring of performance development.

Thus, a more accurate assessment of cardiovascular fitness compared to simpler approaches like shuttle runs and physical working capacity tests for evaluating an individual training status, health, and risk stratification can be ensured (Meyer et al., 2005). Creating reference values for all ages is important for practitioners regarding screening, early intervention, and exercise prescription (Bull et al., 2020; Franklin & Cushman, 2011; Guthold et al., 2020; Piercy et al., 2018). For researchers, such data can be valuable to estimate the fitness of their participants by comparing it to a nationwide sample of the general population or to identify crucial age ranges where cardiovascular fitness declines as a starting point for intervention studies. Therefore, the present work aimed to evaluate the age-related absolute (W) and relative (W/kg) performance levels at LT_{2fix} and LT_{2ind} for cycling within a nationwide sample of adolescents and adults aged 14 to 64 in Germany. A second aim was to create reference standards and percentile curves for the performance at LT_{2fix} and LT_{2ind} for healthcare providers and future studies that are ready to use and openly accessible to both researchers and practitioners.

Material and methods

Study design

The German Health Interview and Examination Survey for Children and Adolescents (KiGGS wave 2, carried out as a combined examination and interview survey) and the German Health Interview and Examination Survey for Adults (DEGS1) are part of the health monitoring programme at the Robert Koch Institute in Germany and included participants from 0 years and older. Data assessment was between 2008 and 2011 for DEGS1 and between 2014 and 2017 for KiGGS wave 2. Participants were recruited in clusters throughout Germany, and the study designs with more specific information have been published elsewhere (Hölling et al., 2012; Scheidt-Nave et al., 2012). The cycle ergometer test with blood analysis for the determination of lactate thresholds was performed with DEGS1 participants up to 64 years of age and with KiGGS wave 2 participants 14 years of age and older if they belonged to the subpopulation of the KiGGS wave 2 examination survey.

Eligibility criteria and ethical approval

KiGGS wave 2 and DEGS1 participants were cleared to participate in the cycle ergometer test using the "Physical Activity Readiness – Questionnaires" (PAR-Q) (Finger et al., 2013). In addition, other medical and physiological contraindications determined during resting blood pressure measurement had to be ruled out in consultation with a medical doctor.

The KiGGS wave 2 and DEGS1 studies conform to the guidelines set out in the Declaration of Helsinki and the German Federal Data Protection Act. The study protocol for DEGS1 was approved by the Charité-Universitätsmedizin Berlin ethics committee in September 2008 (No. EA2/047/08) and consented with the Federal and State Commissioners for Data Protection. The Ethics Commission of the Charité Universitätsmedizin Berlin has reviewed the KiGGS basic survey (No. 101/2000) as well as KiGGS wave 1 (No. EA2/058/09), and the Ethics Commission of the Medizinische Hochschule Hannover has reviewed ethical aspects and approved KiGGS wave 2 (No. 2275-2014). Participation in the studies was voluntary. Participants or their guardians were informed about the aims and contents of the studies as well as about data protection and gave their written consent.

Measurements

Both the KiGGS wave 2 and the DEGS1 trials were conducted on a calibrated cycle ergometer with integrated blood pressure measurement and Polar heart rate monitor (Ergosana CE 0124) (Finger et al., 2013, 2021) using the standardized WHO protocol starting at 25 W with an incremental increase of 25 W every 2 min that is recommended for the general population (Lange Andersen et al., 1971). Participants were instructed to keep a revolution rate of 60–80 rpm throughout the whole trial. Capillary blood was collected from the earlobe in the last seconds of each 2 min stage. Blood lactate concentration for each stage was analyzed utilizing Biosen C-Line Sport (EKF-diagnostic GmbH, Barleben, Germany). The test was stopped if participants reached an exhaustion or stopping criterion (Dickhuth et al., 2011) or at the end of the stage when participants reached 85% maximum heart rate – calculated by 0.85× (220–age) – for DEGS1 and participants of 18 years and older in KiGGS wave 2 and a fixed heart rate of 180 bpm for participants younger than 18 KiGGS wave 2 (Finger et al., 2013). This corresponds to a higher cut-off point for children and younger participants as the risk of high performance increases with age. Exhaustion or stopping criteria assessed by the monitoring study assistant were: Subjective exhaustion, muscular exhaustion with a sustained decrease in pedal cadence to less than 60 revolutions per minute, noticeable paleness, dizziness, headaches, visual disturbances, shortness of breath, decrease in heart rate despite increasing exertion for more than 3 seconds, exceeding blood pressure: 220 mmHg systolic and/or 120 mmHg diastolic, significantly dropping blood pressure (more than 10 mmHg below the initial blood pressure), heart complaints (tightness – 'angina pectoris'), failure of monitoring devices. If a participant experienced subjective symptoms, such as muscular exhaustion that did not yet result in a significant decrease in pedal cadence, the study assistant was instructed to communicate with the participants and if feasible attempt to motivate the participant to continue the ergometry.

Participants' total physical activity was assessed and categorized using the recommendations of the World Health Organization (WHO, 2010).

Participants

The KiGGS wave 2 examination survey included 9877 participants, of whom 5800 were eligible for a bicycle ergometer test with lactate measurement based on their age of at least 14 years. 4914 participants were medically deemed fit for testing and 2438 girls and 2399 boys participated in the ergometer test ($N = 4837$). The DEGS1 trial included 4947 participants of which 3111 passed the PAR-Q screening, and 3030 ($N_{male} = 1488$, $N_{female} = 1542$) participated in the bicycle ergometry. After screening the data for unrealistic outliers and excluding participants with less than 4 completed stages to ensure the adequate fit of the lactate curve, the sample size was reduced to 3428/2496 participants for KiGGS wave 2 and DEGS1, respectively. To assure the correctness of the results, data of all remaining participants were plotted with lactate value on the y-axis and the corresponding power on the x-axis. Manual screening by JF, MT, SH, and SA led to 101/51 exclusions due to unrealistic curves, and the adjustment of 19/12 values to allow for better fitting of the curves for KiGGS wave 2 and DEGS1, respectively. Lastly, 34 of those participants in the KiGGS wave 2 data set were doublets due to being included in the longitudinal study (not the subject of this paper) as well and were therefore removed. A final sample of 3293 participants from the KiGGS wave 2 trial and 2433 participants from the DEGS1 trial was included in the analysis.

Data processing

All data wrangling and processing were conducted in R (R Core Team, 2022) and RStudio (Posit Team, 2023) using tidyverse (Wickham et al., 2019). Lactate thresholds were calculated using the lactater package (Maturana, 2022). Here, we focused on the fixed value of 3 mmol/l for LT_{2fix}, and the LT_{2ind} was calculated as base lactate +1 mmol/l as recommended for the cycle ergometer (L. V. Billat, 1996). For both methods, we included the baseline (step 0) data and used the 3rd-degree polynomial fit. We used both the absolute power (W) as well as the power relative to the weight of the participants (W/kg) for the percentile curves. In addition to LT_{2fix} and LT_{2ind}, we calculated lactate thresholds using the baseline plus method (Berg et al., 1990; Zoladz et al., 1995), the Lactate Turning Point 1 and 2 (LTP 1 and 2) method (Hofmann & Tschakert, 2017; Hofmann et al., 1997; Pokan et al., 1997), and the lactate response (LTratio) (Dickhuth, Yin, et al., 1999) which can be observed in the on the open science framework (https://osf.io/u8h9b/).

After calculating the thresholds, KiGGS wave 2 and DEGS1 data were merged for the statistical analysis and the percentile plots. Further, some participants were excluded in the correspondent analyses due to missing values in weight ($N = 6$) – for relative power – or because they did not reach LT_{2fix} ($N = 479$) or LT_{2ind} ($N = 128$), respectively. The final sample for the statistical analysis included 2389 female and 2801 male participants. We explored age-specific patterns of missing values to limit the possible bias and found no peculiarities.

Statistical analysis

The fitting of the centiles was done using the generalized additive models for location, scale, and shape (GAMLSS) package (Rigby & Stasinopoulos, 2005) as recommended by the WHO (2006). These models allow for different distributions and additive terms to be modeled on the data (Rigby & Stasinopoulos, 2009). We followed the instructions of Stasinopoulos et al., (2008) to build up the models for the percentile curves and reference values. First, we checked for kurtosis of the distributions. As kurtosis was >3 in all cases, we tested the normal (NO), the t family (TF), Box-Cox t (BCT), Gamma (GA), Power Exponential (PE), Generalized Beta type 2 (GB2) and Box-Cox power exponential (BCPE) distributions for the best fit to our data. The best fit based on Akaike Information Criterion (AIC) was for male absolute/relative power at LT_{2ind} BCPE/BCPE and at 3 mmol/l BCPE/BCT, and for female absolute/relative power at LT_{2ind} GA/BCPE and 3 mmol/l BCPE/GA. Then, we tested if a cubic smoothing spline or nonparametric penalized P-splines (Eilers & Marx, 1996) for age would improve the model. The best fit was found for cubic smoothing splines. Therefore, the final model included cubic splines for age as a predictor of respective power. The RS algorithm was used for all models. Diagnostics were checked using the plot() and wp() functions of the GAMLSS package which displayed a good fit of the models. Reference values were extracted using the centiles.pred() function, and percentiles were plotted using the centiles.fan() function at the 2.5, 5, 10, 25, 50, 75, 90, 95, and 97.5th percentile.

Results

Results are displayed separately for LT_{2fix} and LT_{2ind} with both absolute and relative (to weight) power at the respective threshold throughout the lifespan. All accompanied data for the centiles can be found in the appendices A-H. The descriptive data of all participants are displayed in Table 1.

Results for absolute and relative Power at LT_{2fix} and LT_{2ind} can be found in Tables 2 and 3.

Power at the LT_{2fix}

Fitted centile curves for the relative power at LT_{2fix} show that it peaks at the youngest age of 14 years for both male and female participants and declines each year by an average of 0.045 W/kg for males and 0.023 W/kg for females until age 20 before declining more slowly by around 0.009 W/kg for both male and female participants until the maximum age of 64 years. Higher values in men and an average of the 50th percentile of 1.52 W/kg compared to an average of 1.38 W/kg in women can be observed (see Figure 1(a,b)). Absolute power remains fairly stable until the age of 45 after which a slow decline of 0.65/0.43 W per year can be observed in men and women, respectively. Higher values can be observed in men with an average of 122.7 W for the 50th percentile compared to an average of 91.2 W in women (see Figure 1(c,d)).

Power at LT_{2ind}

Fitted centile curves for the fixed LT_{2ind} threshold show that relative power peaks at the youngest age of 14 years for both male and female participants and declines by a mean of 0.040 W/kg for males and 0.016 W/kg for females until age 20 before declining more slowly by around 0.006 W/kg for both male and female participants until the maximum age of 65 years. Higher values in men and an average of the

Table 1. Participant characteristics of the 5199 participants included in the KiGGS wave 2 and DEGS1 studies.

	Male		Female		Total	
	DEGS (*N*=1202)	KiGGS (*N*=1599)	DEGS (*N*=906)	KiGGS (*N*=1492)	DEGS (*N*=2108)	KiGGS (*N*=3091)
Age						
Mean (SD) [Min, Max]	38.5 (12.8) [18.0, 64.0]	18.7 (3.96) [14.0, 29.0]	38.2 (11.9) [18.0, 64.0]	18.5 (3.90) [14.0, 29.0]	38.4 (12.5) [18.0, 64.0]	18.6 (3.93) [14.0, 29.0]
BMI						
underweight	10 (0.8%)	168 (10.5%)	25 (2.8%)	131 (8.8%)	35 (1.7%)	299 (9.7%)
normal weight	501 (41.7%)	1205 (75.4%)	540 (59.6%)	1170 (78.4%)	1041 (49.4%)	2375 (76.8%)
overweight	514 (42.8%)	125 (7.8%)	218 (24.1%)	117 (7.8%)	732 (34.7%)	242 (7.8%)
obese	173 (14.4%)	101 (6.3%)	119 (13.1%)	74 (5.0%)	292 (13.9%)	175 (5.7%)
SES						
low	164 (13.6%)	110 (6.9%)	100 (11.0%)	99 (6.6%)	264 (12.5%)	209 (6.8%)
average	722 (60.1%)	507 (31.7%)	539 (59.5%)	529 (35.5%)	1261 (59.8%)	1036 (33.5%)
high	305 (25.4%)	176 (11.0%)	256 (28.3%)	168 (11.3%)	561 (26.6%)	344 (11.1%)
peak power (W) cycle ergometer test						
Mean (SD) Median [Min, Max]	167 (36.6) 175 [100, 300]	181 (35.8) 175 [100, 300]	120 (20.8) 125 [100, 200]	133 (25.1) 125 [100, 225]	147 (38.6) 150 [100, 300]	158 (39.1) 150 [100, 300]
PA WHO						
guidelines not met	825 (68.6%)	1440 (90.1%)	737 (81.3%)	1388 (93.0%)	1562 (74.1%)	2828 (91.5%)
guidelines met	348 (29.0%)	120 (7.5%)	149 (16.4%)	62 (4.2%)	497 (23.6%)	182 (5.9%)

Ab breviation: BMI = body mass index, SES = socioeconomic status, PA = physical activity, WHO = World Health Organization.

Table 2. Absolute power (watt) at the 25, 50, 75th percentile for the fixed lactate threshold 2 (LT_{2fix}) of 3 mmol/l and the individual lactate threshold 2 (LT_{2ind}) of male and female participants of the KiGGS wave 2 and DEGS1 study.

	Male			Female		
age span	25	50	75	25	50	75
LT_{2fix}						
14–18	109.76	129.43	151.37	84.56	98.50	113.91
19–23	108.18	127.57	149.19	82.14	95.68	110.64
24–28	107.39	126.64	148.10	80.75	94.06	108.78
29–23	107.67	126.97	148.49	80.24	93.47	108.09
34–38	107.44	126.70	148.17	80.33	93.57	108.21
39–43	105.88	124.85	146.02	79.58	92.70	107.20
44–49	103.51	122.07	142.75	77.57	90.36	104.49
49–53	100.34	118.32	138.38	75.15	87.53	101.23
54–58	97.64	115.14	134.66	73.13	85.18	98.51
59–64	94.98	112.01	130.99	71.56	83.36	96.40
LT_{2ind}						
14–18	94.14	112.05	133.27	72.46	84.43	98.05
19–23	92.56	110.17	131.04	71.84	83.71	97.20
24–28	91.86	109.34	130.05	72.05	83.96	97.49
29–23	93.04	110.74	131.71	72.63	84.63	98.28
34–38	93.89	111.75	132.91	73.17	85.26	99.01
39–43	93.05	110.75	131.73	73.02	85.09	98.80
44–49	91.23	108.59	129.16	71.88	83.76	97.26
49–53	88.62	105.48	125.46	70.09	81.68	94.84
54–58	86.97	103.52	123.12	68.32	79.61	92.45
59–64	86.09	102.47	121.87	66.83	77.88	90.43

50th percentile of 1.35 W compared to an average of 1.25 W in women can be observed (see Figure 2(a,b)). Absolute power remains fairly stable throughout the lifespan until the age of 45 after which a slow decline of 0.41/0.31 W can be observed in men and women, respectively. Higher values can be observed in men with an average of 108.5 W for the 50th percentile compared to an average of 83.0 W in women (see Figure 2(c,d)).

Discussion

This work provides age- and sex-specific reference standards and percentile curves for cardiovascular fitness from a sample of 5199 participants (age 14–64) in Germany. As the results of participants above 60 years are based on a limited sample, the reference values for this age group have to be treated with caution. Cardiovascular fitness was assessed on a cycle ergometer based on different lactate threshold concepts.

Table 3. Relative power (Watt/kg) at the 25, 50, 75th percentile for the fixed lactate threshold 2 (LT_{2fix}) of 3 mmol/l and the individual lactate threshold 2 (LT_{2ind}) of male and female participants of the KiGGS wave 2 and DEGS1 study.

	Male			Female		
age span	25	50	75	25	50	75
LT_{2fix}						
14–18	1.609	1.907	2.237	1.406	1.645	1.905
19–23	1.436	1.701	1.996	1.310	1.532	1.775
24–28	1.334	1.580	1.854	1.239	1.450	1.679
29–23	1.288	1.526	1.790	1.197	1.401	1.622
34–38	1.264	1.497	1.757	1.177	1.377	1.595
39–43	1.239	1.468	1.723	1.164	1.362	1.577
44–49	1.220	1.445	1.695	1.141	1.335	1.546
49–53	1.195	1.416	1.661	1.106	1.294	1.499
54–58	1.173	1.390	1.631	1.062	1.243	1.439
59–64	1.151	1.364	1.600	1.013	1.186	1.373
LT_{2ind}						
14–18	1.386	1.654	1.968	1.199	1.409	1.642
19–23	1.232	1.470	1.750	1.138	1.338	1.559
24–28	1.144	1.365	1.625	1.100	1.293	1.507
29–23	1.120	1.336	1.590	1.079	1.268	1.478
34–38	1.114	1.330	1.582	1.068	1.255	1.463
39–43	1.098	1.310	1.558	1.063	1.250	1.457
44–49	1.081	1.290	1.535	1.053	1.238	1.443
49–53	1.059	1.264	1.504	1.026	1.206	1.406
54–58	1.047	1.250	1.487	0.985	1.158	1.350
59–64	1.043	1.245	1.481	0.938	1.102	1.285

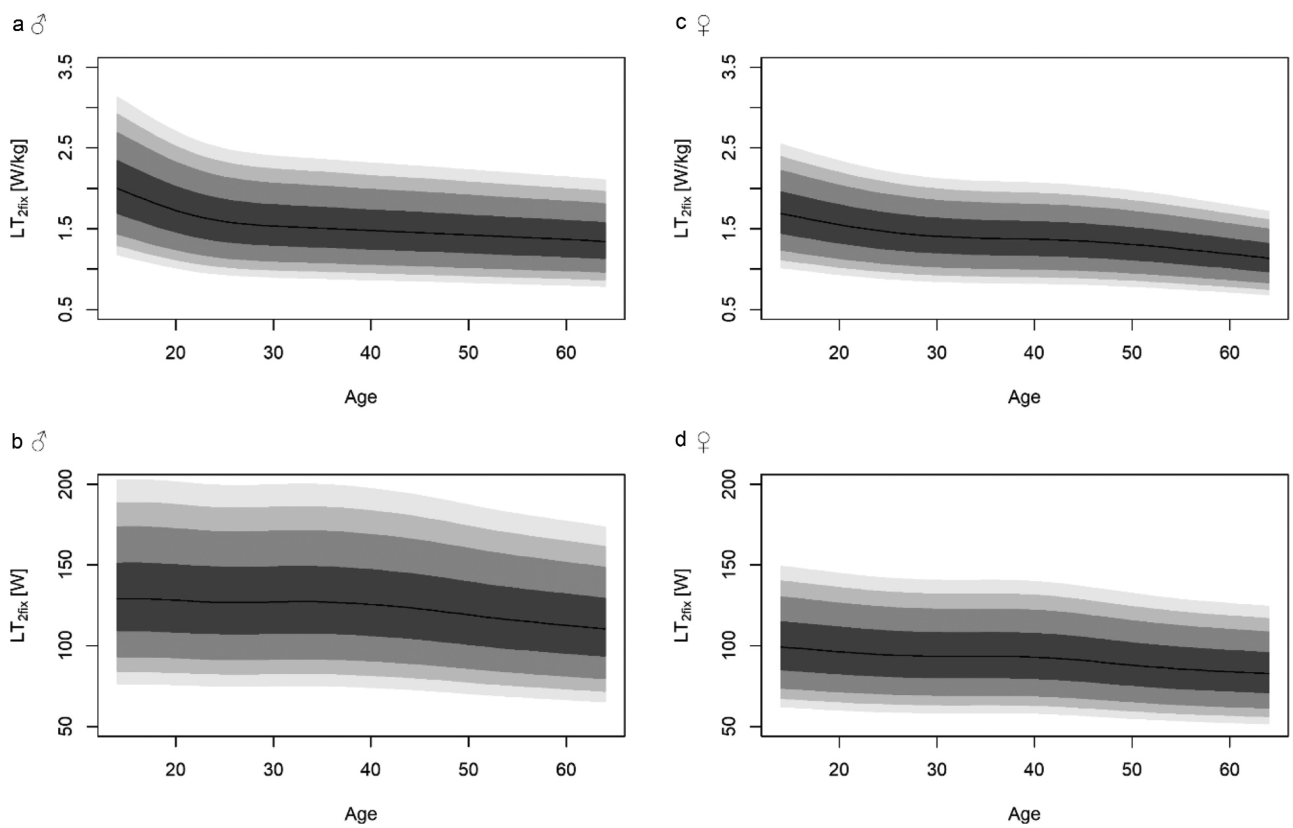

Figure 1. Centile curves at the 2.5, 5, 10, 25, 50, 75, 90, 95, and 97.5th percentile for relative power (a, b) and absolute power (c, d) at fixed lactate threshold 2 (LT_{2fix}) of 3 mmol/l for male (a, c) and female (b, d) participants of the KiGGS wave 2 and DEGS1 study. Note. Values for females over 60 years are based on less than 10 participants.

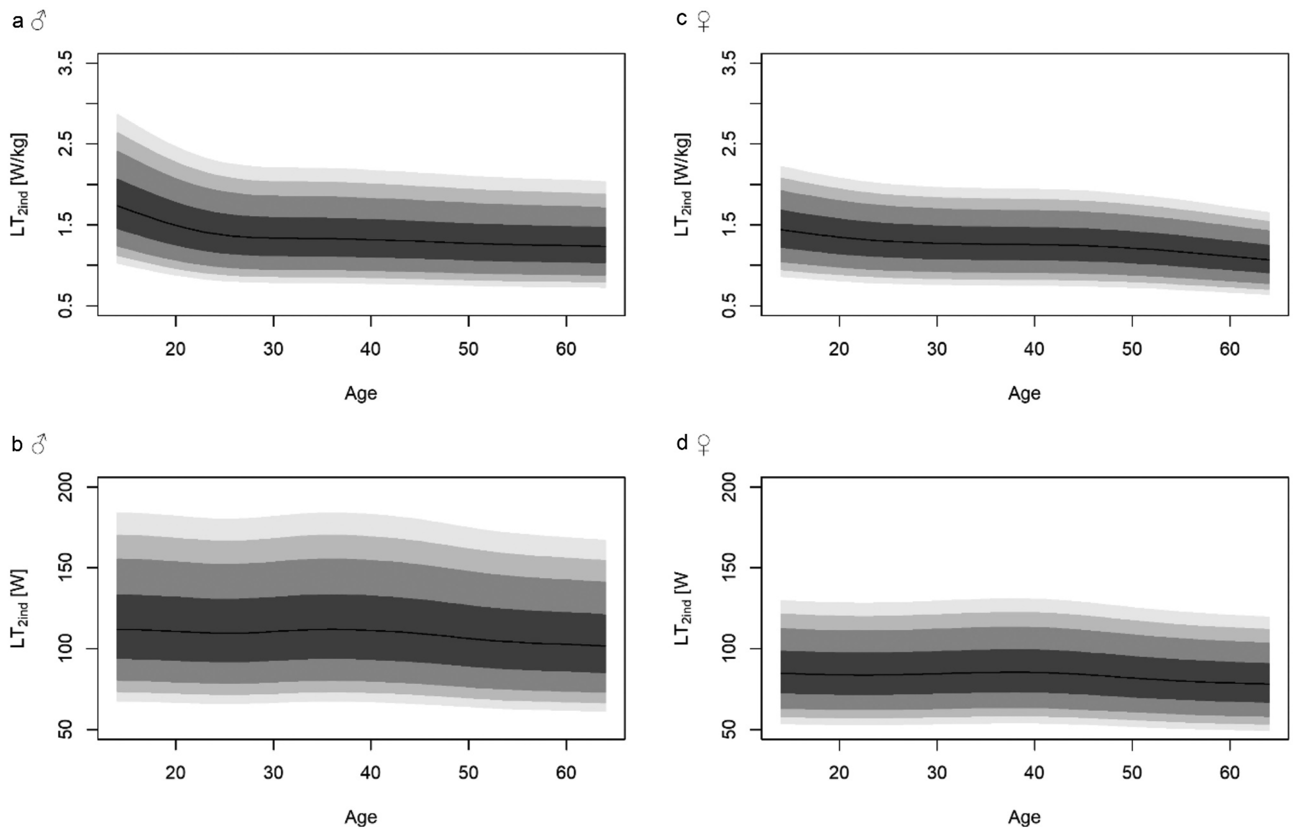

Figure 2. Centile curves at the 2.5, 5, 10, 25, 50, 75, 90, 95, and 97.5th percentile for relative power (a, b) and absolute power (c, d) at the individual lactate threshold 2 (LT_{2ind}) for male (a, c) and female (b, d) participants of the KiGGS wave 2 and DEGS1 study. Note. Values for females over 60 years are based on less than 10 participants.

The LT_{2ind} was estimated at lower power compared to the LT_{2fix} for both male and female participants. Absolute power (W) at the LT_{2ind} and LT_{2fix} was found to be relatively stable until the age of 45 after which a slow decline can be observed. Relative power at the thresholds (W/kg) peaked at the youngest age and declined until age 20 where the slope reduced until the maximum age of 64 which, if compared to the absolute power, has to be related to the gain in weight throughout the lifespan, especially in the early years in the data. These reference standards of the normal population with an average to low physical activity profile will help to identify and classify performance at the lactate threshold 2 for participants of health-related studies and enable early interventions in clinical practice. A benefit of this study is that all data – without the microdata for weight and height due to privacy concerns but additionally including data on other threshold concepts – are openly accessible on the open science framework (https://osf.io/u8h9b/).

Male participants showed higher power – both relative and absolute – at the threshold compared to female participants of all ages. This can be attributed to biological reasons, mainly sex chromosomes, and sex hormones, in particular testosterone (Hunter et al., 2023). The sex difference is comparable to the difference in cardiovascular fitness measured by the 20 m shuttle-run test, the physical work capacity test in children and adolescents (Niessner et al., 2020; Ortega et al., 2023), the 6-minute walk test, the stair test (Tveter et al., 2014), and ventilatory thresholds (Vainshelboim et al., 2020) in adults. The current study expands previous knowledge by providing reference values for both children and adults with the same measurement and by considering the concept of lactate thresholds.

Concerning cardiovascular fitness throughout the lifespan, the finding of a relatively stable absolute power with only a slow decline after the age of 45 at the thresholds is somewhat surprising, while the decline of relative power was expected and is well described through the literature (Ortega et al., 2023; Vainshelboim et al., 2020). As most studies use relative values like relative VO2max (ml $O_2 * kg^{-1} * min^{-1}$) for better comparison across samples, absolute values like speed (e.g., km/h) or resistance (e.g., W) can also be beneficial as they are easier to communicate in training practice. A study by Niessner et al., (2020) found that the absolute performance of children between 6 and 18 years on a cycle ergometer using the physical working capacity test at a heart rate of 170 bpm, increased steadily for boys until the age of 16 where the increase slowed down, while performance in girls increased until the age of 13 after which the slope flattened. This difference can be attributed to the different development stages of boys and girls during puberty (Lloyd et al., 2014). In the sample of the current study, which started at the age of 14, this difference is not evident which might be caused by the limited age range and the difference between heart rate-based assessments – which can fluctuate highly between individuals at the same performance level (Achten & Jeukendrup, 2003) – and lactate based assessments. What the current study adds is, that throughout adolescence until the age of 45, absolute performance at the threshold remains relatively stable and only slowly declines afterward. This can be attributed to aging-related factors like the decline in cardiac output (Weiss et al., 2006), mitochondrial function (Short & Nair, 2001), and physical activity which were found to be responsible for the decline of aerobic capacity.

Of relevance for exercise physiology testing is the finding, that the LT_{2ind}- calculated as base lactate +1 mmol/l as recommended for the cycle ergometer (L. V. Billat, 1996) – was consistently reached at a lower power than the fixed 3 mmol/l threshold. This difference was 17/15 W at age 14 and declined with age but was still at around 9/4 W at age 64 for male and female participants respectively. Therefore, the choice of threshold estimation has to be considered especially if working with younger participants. This was also pointed out by the evaluation of the concordance of different threshold estimations by Arratibel-Imaz et al., (2016) who found that the LT_{2fix} at 4 mmol/l produced higher results compared to estimations of LT_{2ind} and that the latter method has a higher agreement than LT_{2fix} with maxLASS on a cycle ergometer. Further, important factors that can influence the threshold estimation like test protocol, ergometer type, expertise in blood sampling, nutritional status of participants, and others have to be considered when comparing different data.

Strengths and limitations

Strengths of this examination include the assessment of cardiovascular fitness with an accurate metabolism-based method that has a high value for scientific and clinical practice. Further strengths are the large and nationwide sample, pooling data for adolescents and adults, the reporting on multiple thresholds and the supply of data that can be used for further analyses, and the application of the recommended GAMMLs method (WHO, 2006) for estimating the reference values and percentile curves. There are also some limitations to acknowledge. First of all, even though the main data sets with nearly 15,000 participants consist of a representative sample of the German population, the subsample with valid data points for this manuscript is limited to the 5199 who were medically deemed fit for testing and provided enough data to be included in the analysis. This limits the representativeness of the data, especially for the older age groups. Here, the reference values, e.g., for female participants between 60 and 64 are based on less than $N = 10$ for each year in this examination. The reason for this might be that one of the exhaustion criteria was based on reaching 85% maximum heart rate. For participants 60+ or highly trained individuals, this might have led to the stop of the test before they reached the required 4 completed stages of the protocol except for participants with a higher fitness level. Therefore, the results of this age group have to be treated with caution, and the reported power estimates are likely higher than those in the German population. However, we explored, e.g., the BMI of older participants and found no bias towards a lower BMI in this group. Third, the data are cross-sectional and not longitudinal data, therefore no conclusions about individual developments across the age span can be given. Lastly, data were pooled from two studies that started 6 years apart which could also influence the comparison of the results due to secular trends. As data assessment was consistent within these studies concerning the ergometer testing parameters and blood lactate analysis, the error is likely limited.

Conclusion

The age- and sex-specific reference values for absolute and relative power at the LT_{2ind} and LT_{2fix} show higher power values at LT_{2fix} compared to LT_{2ind} and for men compared to women, and different patterns for absolute and relative power across the age span. These reference standards provided by this study add important information for research, fitness, and clinical practice. The supply of the results for additional threshold concepts adds to the widespread application of the present work.

Abbreviations

LT_{2fix}	fixed lactate threshold 2
LT_{2ind}	individual lactate threshold 2
kg	kilogram
maxLASS	maximal lactate steady state
mmol/l	minimoles per liter
PAR-Q	Physical Activity Readiness – Questionnaires
VO2max	maximal oxygen uptake capacity
W	Watt
WHO	World Health Organization

Acknowledgments

The authors would like to thank the Research Data Center of the RKI for providing the data and Jonas Finger for his preliminary scientific work. The authors acknowledge and thank Felipe Mattioni Maturana for his support and the implementation of the base lactate +1 mmol/l threshold into the lactater package.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The study was funded by the Robert Koch Institute and the Federal Ministry of Health.

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Data availability statement

The datasets used for the analyses of the current study are available in the Open Science Framework repository, https://doi.org/10.17605/OSF.IO/U8H9B

Open scholarship

This article has earned the Center for Open Science badges for Open Data and Open Materials through Open Practices Disclosure. The data and materials are openly accessible at https://osf.io/u8h9b/.

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