

Aerobic Capacity Reference Data in 3816 Healthy Men and Women 20–90 Years

Henrik Loe^{1,2}, Øivind Rognmo¹, Bengt Saltin³, Ulrik Wisløff^{1*}

1 K.G. Jebsen Center of Exercise in Medicine at Department of Circulation and Medical Imaging, NTNU, Trondheim, Norway, **2** Valnesfjord Rehabilitation Center, Valnesfjord, Norway, **3** Copenhagen Muscle Research Centre, University Hospital, Copenhagen, Denmark

Abstract

Purpose: To provide a large reference material on aerobic fitness and exercise physiology data in a healthy population of Norwegian men and women aged 20–90 years.

Methods: Maximal and sub maximal levels of VO_2 , heart rate, oxygen pulse, and rating of perceived exertion (Borg scale: 6–20) were measured in 1929 men and 1881 women during treadmill running.

Results: The highest $\text{VO}_{2\text{max}}$ and maximal heart rate among men and women were observed in the youngest age group (20–29 years) and was $54.4 \pm 8.4 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and $43.0 \pm 7.7 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ (sex differences, $p < 0.001$) and $196 \pm 10 \text{ beats} \cdot \text{min}^{-1}$ and $194 \pm 9 \text{ beats} \cdot \text{min}^{-1}$ (sex differences, $p < 0.05$), respectively, with a subsequent reduction of approximately $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and $6 \text{ beats} \cdot \text{min}^{-1}$ per decade. The highest oxygen pulses were observed in the 3 youngest age groups (20–29 years, 30–39 years, 40–49 years) among men and women; $22.3 \text{ mL} \cdot \text{beat}^{-1} \pm 3.6$ and $14.7 \text{ mL} \cdot \text{beat}^{-1} \pm 2.7$ (sex differences, $p < 0.001$), respectively, with no significant difference between these age groups. After the age of 50 we observed an 8% reduction per decade among both sexes. Borg scores appear to give a good estimate of the relative exercise intensity, although observing a slightly different relationship than reported in previous reference material from small populations.

Conclusion: This is the largest European reference material of objectively measured parameters of aerobic fitness and exercise-physiology in healthy men and women aged 20–90 years, forming the basis for an easily accessible, valid and understandable tool for improved training prescription in healthy men and women.

Citation: Loe H, Rognmo Ø, Saltin B, Wisløff U (2013) Aerobic Capacity Reference Data in 3816 Healthy Men and Women 20–90 Years. PLoS ONE 8(5): e64319. doi:10.1371/journal.pone.0064319

Editor: Alejandro Lucia, Universidad Europea de Madrid, Spain

Received: February 27, 2013; **Accepted:** April 10, 2013; **Published:** May 15, 2013

Copyright: © 2013 Loe et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Funding: This study was funded by K.G. Jebsen Foundation, The Norwegian Council on Cardiovascular Disease, The Research Council of Norway (funding for Outstanding Young Investigators (UW) and scholarship (HL)), Foundation for Cardiovascular Research at St. Olav's Hospital, Norwegian State Railways, Roche Norway Incorporated and Valnesfjord Rehabilitation Center. There are no disclosures to report or any conflicts of interest. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors are declaring a commercial funder, Roche Norway Incorporated. This does not alter the authors' adherence to all the PLOS ONE policies on sharing data and materials.

* E-mail: ulrik.wisloff@ntnu.no

Introduction

Evidence supports a strong inverse association between cardiorespiratory fitness and all-cause mortality [1–4]. Therefore, in order to increase the individual's fitness level, different types of exercise training are used both in prevention and treatment of cardiovascular and life-style related disease [5]. In order to prescribe a proper prevention- or treatment program either, the more reliable, individually cardiopulmonary exercise testing is needed [6,7], or one can rely upon previously established reference material. Most previous studies measuring cardiorespiratory fitness tend to use peak oxygen uptake ($\text{VO}_{2\text{peak}}$), indirect methods, estimation by equation, selected populations and/or small sample sizes [8–15]. Previously established variables suitable for exercise prescription such as oxygen uptake, heart rate, Watts and Borg scale scores, are mostly based upon small sample sizes or poorly described populations [6,16–23]. The aim of this study was to establish a large reference material of empirical cardiorespiratory fitness and exercise-physiology data in healthy men and women

aged 20–90 years in order to provide an easily accessible, valid and understandable tool for improved exercise training prescription.

Methods

Participants

The HUNT 3 fitness study is the third wave of the Nord-Trøndelag Health Studies (www.ntnu.edu/hunt). Data were collected between October 2006 and June 2008. The entire population >20 years of age ($n = 94194$) were invited to participate, 54% ($n = 50821$) accepted. The HUNT 3 Fitness Study was designed to acquire reference material for submaximal and maximal cardiorespiratory parameters in a healthy population. Exclusion criteria were cancer, cardiovascular disease, obstructive lung disease and use of blood pressure medication. Participants also had to be cleared in a brief medical interview. Based upon self-reported information, 30513 candidates presented as suitable for $\text{VO}_{2\text{max}}$ testing. Out of these, 12609 candidates

resided in the 3 municipalities selected for $\text{VO}_{2\text{max}}$ testing, and 5633 of them volunteered to participate. These 3 locations were chosen due to geographical location to minimize travel distance for participants. 4621 candidates completed a $\text{VO}_{2\text{max}}$ test, whereas 3816 tests were considered to have reached the true $\text{VO}_{2\text{max}}$.

Ethics Statement

The study was approved by the Regional committee for medical research ethics (2012/1228/REK midt), the Norwegian Data Inspectorate and the National Directorate of Health, and is in compliance with the Helsinki declaration. Written informed consent was obtained from all participants.

$\text{VO}_{2\text{max}}$ and Heart Rate

An individualized graded protocol [24] was used for measuring $\text{VO}_{2\text{max}}$ (Cortex MetaMax II, Cortex, Leipzig, Germany). Prior to starting the testing procedure several MetaMax II apparatus were tested against Douglas-bag and iron lung (Cortex, Leipzig, Germany). Two MetaMax II apparatus were returned to Cortex due to unstable recordings (both ventilation and carbon dioxide analysis) and replaced by two new apparatus that were tested and found both reliable and valid. Hence, all MetaMax apparatus used in the project were both valid and reliable. Test-retest correlation of oxygen-uptake for the tested-personnel in the project was 0.99, $p < 0.001$ and coefficient of variation was 1.8%. Bland-Altman plot were constructed where differences in two tests of maximal oxygen uptake (and sub maximal) from each person (test-1 minus test-2) were plotted against the average of the two tests $((\text{test-1} + \text{test-2})/2)$. Average difference was $-0.04 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ and standard deviation of the difference was 1.0. Therefore one can expect that 95% of all observations are at the average $((\text{test-1} + \text{test-2})/2) \pm 2$ standard deviations. Thus, we can expect values to vary between $-0.04 - 2 \cdot 1$ to $-0.04 + 2 \cdot 1$ if we test maximal oxygen uptake twice in the same person within a short time period. Velocity and inclination of the test treadmills were calibrated prior to testing.

The MetaMax II was calibrated prior to the first test each day using a standard two-point gas calibration procedure recommended by the manufacturer. The calibration includes measurements of ambient air and a gas mix of known content (15.03% O_2 and 4.98% CO_2 in N_2), a calibration of the Triple-V volume transducer with a calibrated 3 L syringe (Calibration syringe D, Sensormedics, CareFusion, San Diego, CA, USA), and barometric pressure control. Volume calibration was implemented every third test and the two-point gas calibration every fifth. Before each test the ambient room air was routinely checked. Heart rate was measured by radio telemetry (Polar S610i, Polar Electro Oy, Kempele, Finland). Body mass was measured using the weighing scale Model DS-102 (Arctic Heating AS, Nøtterøy, Norway). All participants had a treadmill familiarization period of 8–10 minutes during warm-up. They were instructed to avoid grabbing handrails if not necessary. The individualized warm-up workload determined the initial velocity/inclination on the subsequent treadmill test. Candidates wore a face mask (Hans Rudolph, Germany) linked to the MetaMax II. When participant maintained a stable oxygen uptake > 30 seconds, velocity (0.5–1.0 $\text{km}\cdot\text{h}^{-1}$) or inclination (1–2%) were increased. Increased workload was preferably obtained with increased velocity and keeping a fixed slope angle. If a participant was unable to increase velocity, inclination was increased. The average velocity and slope during test protocol were $6.8 \pm 2.2 \text{ km}\cdot\text{h}^{-1}$ (range 2–17 $\text{km}\cdot\text{h}^{-1}$) and $10.0 \pm 1.6\%$ (range 2–16%), respectively. Tests were terminated when candidates were exhausted or reached a VO_2 plateau that remained stable despite increased work load [25], i.e. VO_2 did not

increase more than $2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ despite increased work load.

Ventilatory Equivalent

We calculated the ventilatory equivalent ($V_E \cdot \text{VO}_2^{-1}$) at $\text{VO}_{2\text{max}}$. The ventilatory equivalent describes the fraction of minute ventilation (V_E) to oxygen uptake (VO_2), hence, the higher the value the more ineffective is the V_E . At higher levels of increasingly harder submaximal workloads, a disproportionate increase in V_E relative to VO_2 occurs. This heralds an increasingly more inefficient V_E .

Questionnaire-based Information

Physical activity index score (PAI) was calculated from replies in a self-administered questionnaire that consisted of 3 questions. Question 1: “How frequently do you exercise?” with response alternatives “Never” (0); “Less than once a week” (0); “Once a week” (1); “2–3 times a week” (2.5); “Almost every day” (5). Question 2: “If you exercise as frequently as once or more times a week: How hard do you push yourself?” with response alternatives “I take it easy without breaking a sweat or losing my breath” (1); “I push myself so hard that I lose my breath and break into sweat” (2); “I push myself near exhaustion” (3). Question 3: “How long does each session last?” with the following response options “Less than 15 minutes” (0.1); “15–29 minutes” (0.38); “30 minutes to 1 hour” (0.75); “More than 1 hour” (1.0). The numbers in brackets, corresponding to each subject’s response to the 3 questions above, were multiplied to calculate the physical activity index score. An index score in the range 0.05–1.50 was considered to signify low activity, an index score in the range 1.51–3.75 was interpreted as medium activity and a score in the range 3.76–15.0 signified high activity. The index score is previously established as valid and reliable [26].

Borg Scale of Perceived Exertion and VO_2 at 2 Sub Maximal and Maximal Workload

Candidates were asked to state their subjective rating of perceived exertion (Borg scale) at the end of 3 different levels. Borg scale visualizes work load intensity, denoted by numbers 6–20 [22], with a proportional relation between increased rating of perceived exertion and the reported Borg scale number. Level 1: The individual initial workload for the test was determined during warm-up. All individuals reached a stable VO_2 and heart rate after 3 minutes at the first submaximal work load. Level 2: Treadmill gradient was elevated by 2% or velocity increased $1 \text{ km}\cdot\text{h}^{-1}$. After 1–2 minutes at this sub maximal workload steady state was obtained. The maximum level is described previously.

Watts

Workload in watts was calculated at the 3 described workloads. Calculations were based on treadmill slope gradient, velocity and body mass input in Cortex MetaMax II (Cortex, Leipzig, Germany). Minimum slope gradient was 2% and mean slope gradient at maximum workload was $10.4 \pm 1.4\%$.

Statistical Analysis

Parametric analysis was used based on the large sample size. QQ-plots supported the assumption of normally distributed data. Descriptive data are presented as arithmetic mean \pm standard deviation. An Independent-Samples T test was used for establishing level of significance between sexes and age groups. Linear regression, with 95% confidence interval, was used to illustrate associations between physiological parameters. All statistical tests

were two-sided. SPSS 16.0 (Statistical package for Social Sciences, Chicago; Illinois, USA) and GraphPad Prism 4.01 (GraphPad Software, San Diego, California, USA) were used to analyze data. Correlations were done using data from Level 1, Level 2 and Level 3 (maximum) as described above. A p-value of <0.05 was considered statistically significant.

Results

Overall $\text{VO}_{2\text{max}}$ was $3.19 \pm 0.90 \text{ L} \cdot \text{min}^{-1}$ or $41.3 \pm 9.2 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ (range 18.6–76.5 $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, Table 1). Women had 18.7% ($p < 0.001$) lower $\text{VO}_{2\text{max}}$ than men ($37.0 \pm 7.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ vs. $45.4 \pm 8.9 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$). Maximal oxygen pulse was 34% lower ($p < 0.001$) in women than men ($14.0 \pm 2.6 \text{ mL} \cdot \text{beat}^{-1}$ vs. $21.1 \pm 3.8 \text{ mL} \cdot \text{beat}^{-1}$). Maximal workload at $\text{VO}_{2\text{max}}$ was 33% lower ($p < 0.001$) in women compared with men ($121 \pm 24 \text{ W}$ vs. $181 \pm 36 \text{ W}$). There were no significant sex differences in maximal heart frequencies or Borg scores at termination of the test (Table 1).

The highest $\text{VO}_{2\text{max}}$ and maximal heart rate for both sexes were observed in the age group 20–29 years. Among men and women in this age group $\text{VO}_{2\text{max}}$ were $54.4 \pm 8.4 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and $43.0 \pm 7.7 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ (sex differences, $p < 0.001$) with corresponding heart rates of $196 \pm 10 \text{ beats} \cdot \text{min}^{-1}$ and $194 \pm 9 \text{ beats} \cdot \text{min}^{-1}$ (sex differences, $p < 0.05$). In both sexes $\text{VO}_{2\text{max}}$ and maximal heart rates were approximately 8% ($\approx 3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) and 3.5% ($6 \text{ beats} \cdot \text{min}^{-1}$) lower per increased decade, respectively. The Physical Activity Index (PAI) scores were also highest for both sexes in this age group. For men and women PAI scores were 4.64 ± 4.04 and 3.96 ± 3.25 , respectively (no significant sex differences), which are considered to indicate a high physical activity level. All other age groups,

regardless of sex, had PAI scores in the range 2.67–3.70, which are considered to indicate medium activity [26] (Table 2).

We observed an $\text{EqVO}_{2\text{max}}$ of 33.9 ± 4.0 and 34.1 ± 5.3 among men and women, aged 20–29 years, respectively. Generally no differences were found between sexes and age groups, except from a 3% ($p < 0.05$) higher $\text{EqVO}_{2\text{max}}$ in females aged 30–39 and 40–49 years compared to corresponding groups of males. Additionally, $\text{EqVO}_{2\text{max}}$ increased by 3% ($p < 0.05$) between the two most senior male groups (Table 2).

The highest maximal oxygen pulse was observed in the 3 youngest age groups (20–49 years) for both sexes, with no significant difference between these age groups. Women in these age groups had 33% lower ($p < 0.001$) oxygen pulse compared with men ($14.7 \pm 2.7 \text{ mL} \cdot \text{beat}^{-1}$ vs. $22.3 \pm 3.6 \text{ mL} \cdot \text{beat}^{-1}$). In the subsequent age groups an approximately 8% reduction in oxygen pulse per decade was observed among both sexes (Table 3).

Rating of Perceived Exertion, % $\text{VO}_{2\text{max}}$ and %maximal Heart Rate

As can be seen from Table 4, rating of perceived exertion reported as Borg Score fairly well estimate the relative exercise intensity expressed as percent of maximal heart rate and percent of $\text{VO}_{2\text{max}}$. Data also show that there may be sex differences in these relationships in the lowest intensities corresponding to Borg below 16. For example the actual exercise intensity for men and women that report to exercise at Borg 6–9 corresponds to 75.8% (CI: 74.5–77.1) and 79.1% (CI: 77.6–80.5) of maximal heart rate, respectively (sex differences, $p < 0.05$). Furthermore, Borg 13–15 corresponds to a heart rate of 84.7% (CI: 84.3–85.1) for men and 88.4% (CI: 88.0–88.7) for women (sex differences, $p < 0.001$). The same discrepancies apply to % $\text{VO}_{2\text{max}}$ in corresponding Borg range. At Borg Score above 16 there were no sex or age group differences, with the exception of an age group difference between the 50–59 years and the 60–69 years group in both percent of maximal heart rate ($p < 0.01$) and percent of $\text{VO}_{2\text{max}}$ ($p < 0.05$).

VO_2 , Heart Rate, Watt and Physical Activity Index

Figure 1 displays the relationship between VO_2 and heart rate. The overall correlation for VO_2 ($\text{L} \cdot \text{min}^{-1}$) and heart rate was found to be moderate ($r = 0.51$, $p < 0.0001$). Stratified by sex, this association became stronger; males $r = 0.70$ ($p < 0.0001$), female $r = 0.61$ ($p < 0.0001$). The association between percent VO_2 and percent maximal heart rate was strong; all $r = 0.89$ ($p < 0.0001$), male $r = 0.90$ ($p < 0.0001$), female $r = 0.87$ ($p < 0.0001$).

Figure 2 demonstrates the strong association between VO_2 ($\text{L} \cdot \text{min}^{-1}$) and treadmill workload (Watts), and the correlation between watts and heart rate; VO_2 vs. Watts: all $r = 0.90$ ($p < 0.0001$), male $r = 0.89$ ($p < 0.0001$), female $r = 0.84$ ($p < 0.0001$). Heart rate vs. Watts: Viewing the full sample size a moderate correlation was observed between treadmill workload (Watts) and heart rate ($r = 0.55$, $p < 0.0001$). Good correlations were observed when the data was stratified by sex; male $r = 0.71$ ($p < 0.0001$), female $r = 0.66$ ($p < 0.0001$).

Figure 3 demonstrates a poor, but statistically strong association between Physical activity index and VO_2 ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$); all $r = 0.24$ ($p < 0.0001$), male $r = 0.29$ ($p < 0.0001$) and female $r = 0.27$ ($p < 0.0001$).

Figure 4 exhibits a moderate association between VO_2 (both $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and $\text{L} \cdot \text{min}^{-1}$) and age groups, male: $r = 0.54$ and $r = 0.54$, respectively; female: $r = 0.52$ and $r = 0.50$, respectively.

Table 1. Physical and physiological characteristics of participants in the HUNT 3 Fitness study.

	All (n = 3678)	Male (n = 1929)	Female (n = 1881)
Age (years)	46.7 ± 13.1	47.5 ± 13.1	45.8 ± 13.0
Body mass(kg)	77.3 ± 13.7	85.3 ± 11.1	69.2 ± 11.0
Height (cm)	172.9 ± 9.0	179.5 ± 6.4	166.1 ± 5.8
$\text{VO}_{2\text{max}}$ ($\text{L} \cdot \text{min}^{-1}$)	3.19 ± 0.90	3.83 ± 0.72	2.53 ± 0.49
$\text{VO}_{2\text{max}}$ ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	41.3 ± 9.2	45.4 ± 8.9	37.0 ± 7.5
$\text{VO}_{2\text{max}}$ ($\text{mL} \cdot \text{kg}^{-0.75} \cdot \text{min}^{-1}$)	122.0 ± 27.8	137.3 ± 25.6	106.2 ± 20.2
O_2 pulse ($\text{mL} \cdot \text{beat}^{-1}$)	17.7 ± 4.9	21.1 ± 3.8	14.0 ± 2.6
R ($\text{CO}_2 \cdot \text{VO}_2^{-1}$)	1.14 ± 0.05	1.14 ± 0.05	1.14 ± 0.05
f_c ($\text{beats} \cdot \text{min}^{-1}$)	181 ± 14	182 ± 14	181 ± 14
Work load (Watts)	151 ± 43	181 ± 36	121 ± 24
Borg	18 ± 1	18 ± 1	18 ± 1
Physical activity index	3.41 ± 2.88	3.31 ± 2.99	3.52 ± 2.76

Data is presented as arithmetic mean ± SD. $\text{VO}_{2\text{max}}$: maximal oxygen uptake, O_2 pulse: oxygen uptake per heartbeat, CO_2 : Carbon dioxide, R: respiratory exchange ratio, f_c : cardiac frequency, workload: treadmill exercise load, BORG: subjective perception of fatigue (6–20), Physical activity index: A weighted product score between training-intensity, duration and frequency.
doi:10.1371/journal.pone.0064319.t001

Table 2. Physiological variables in the HUNT 3 Fitness study stratified by sex and age groups.

	Male	Female
	20–29 years	
	(n = 199)	(n = 215)
VO _{2max} (L·min ⁻¹)	4.32±0.71	2.78±0.46
VO _{2max} (mL·kg ⁻¹ ·min ⁻¹)	54.4±8.4	43.0±7.7
VO _{2max} (mL·kg ^{-0.75} ·min ⁻¹)	162.1±23.7	121.7±20.1
EqVO _{2max} (V _E ·VO _{2max} ⁻¹)	33.9±4.0	34.1±5.3
Body mass (kg)	80.1±10.6	65.5±10.4
Height (cm)	181±6	166±6
R (CO ₂ ·VO ₂ ⁻¹)	1.15±0.05	1.15±0.05
f _c (beats·min ⁻¹)	196±10	194±9
Workload (Watts)	200±39	128±24
BORG	19±1	18±1
PAI	4.64±4.03	3.96±3.25
	30–39 years	
	(n = 324)	(n = 359)
VO _{2max} (L·min ⁻¹)	4.22±0.63	2.75±0.48
VO _{2max} (mL·kg ⁻¹ ·min ⁻¹)	49.1±7.5	40.0±6.8
VO _{2max} (mL·kg ^{-0.75} ·min ⁻¹)	149.2±21.0	114.9±18.1
EqVO _{2max} (V _E ·VO _{2max} ⁻¹)	33.2±3.7	34.1±4.6
Body mass (kg)	86.8±12.1	69.7±11.5
Height (cm)	180±6	168±5
R (CO ₂ ·VO ₂ ⁻¹)	1.15±0.05	1.15±0.05
f _c (beats·min ⁻¹)	190±9.5	188±11
Workload (Watts)	197±33	128±23
BORG	18±1	18±1
PAI	3.15±3.23	3.36±2.73
	40–49 years	
	(n = 526)	(n = 493)
VO _{2max} (L·min ⁻¹)	4.03±0.61	2.65±0.44
VO _{2max} (mL·kg ⁻¹ ·min ⁻¹)	47.2±7.7	38.4±6.9
VO _{2max} (mL·kg ^{-0.75} ·min ⁻¹)	143.3±21.4	110.3±18.1
EqVO _{2max} (V _E ·VO _{2max} ⁻¹)	33.6±4.3	34.6±4.5
Body mass (kg)	86.4±11.5	69.9±11.2
Height (cm)	180±7	167±6
R (CO ₂ ·VO ₂ ⁻¹)	1.15±0.05	1.15±0.05
f _c (beats·min ⁻¹)	184±11	182±11
Workload (Watts)	189±33	125±22
BORG	18±1	18±1
PAI	3.00±2.73	3.70±2.66
	50–59 years	
	(n = 466)	(n = 428)
VO _{2max} (L·min ⁻¹)	3.65±0.59	2.36±0.37
VO _{2max} (mL·kg ⁻¹ ·min ⁻¹)	42.6±7.4	34.4±5.7
VO _{2max} (mL·kg ^{-0.75} ·min ⁻¹)	129.5±21.1	98.7±15.0
EqVO _{2max} (V _E ·VO _{2max} ⁻¹)	33.9±4.9	33.9±4.2
Body mass (kg)	86.4±10.3	69.6±10.2
Height (cm)	179±6	165±6
R (CO ₂ ·VO ₂ ⁻¹)	1.14±0.05	1.14±0.05

Table 2. Cont.

	Male	Female
	20–29 years	
	(n = 199)	(n = 215)
f _c (beats·min ⁻¹)	177±12	176±11
Workload (Watts)	173±28	117±23
BORG	18±1	18±1
PAI	3.24±2.70	3.52±2.80
	60–69 years	
	(n = 300)	(n = 240)
VO _{2max} (L·min ⁻¹)	3.30±0.55	2.16±0.33
VO _{2max} (mL·kg ⁻¹ ·min ⁻¹)	39.2±6.7	31.1±5.1
VO _{2max} (mL·kg ^{-0.75} ·min ⁻¹)	118.5±19.4	89.6±13.4
EqVO _{2max} (V _E ·VO _{2max} ⁻¹)	34.9±5.0	34.1±4.4
Body mass (kg)	84.7±9.9	70.4±10.9
Height (cm)	179±6	165±5
R (CO ₂ ·VO ₂ ⁻¹)	1.14±0.05	1.12±0.05
f _c (beats·min ⁻¹)	171±13	169±12
Workload (Watts)	160±33	110±23
BORG	17±1	17±2
PAI	3.22±2.58	3.19±2.57
	+70 years	
	(n = 76)	(n = 53)
VO _{2max} (L·min ⁻¹)	2.81±0.50	1.85±0.35
VO _{2max} (mL·kg ⁻¹ ·min ⁻¹)	35.3±6.5	28.3±5.2
VO _{2max} (mL·kg ^{-0.75} ·min ⁻¹)	105.3±18.5	80.3±13.8
EqVO _{2max} (V _E ·VO _{2max} ⁻¹)	36.0±5.2	34.9±4.4
Body mass (kg)	80.2±9.6	66.2±11.2
Height (cm)	176±6	162±6
R (CO ₂ ·VO ₂ ⁻¹)	1.12±0.05	1.11±0.03
f _c (beats·min ⁻¹)	163±15	165±16
Workload (Watts)	140±31	97±26
BORG	17±1	16±2
PAI	3.46±2.92	2.67±1.92

Data is presented as arithmetic mean ± SD. VO_{2max}: maximal oxygen uptake, EqVO_{2max}: ventilatory equivalents, R: respiratory exchange ratio, f_c: cardiac frequency, Workload: treadmill exercise load, BORG: subjective perception of fatigue (6–20), PAI: physical activity index: A weighted product score between training- intensity, duration and frequency.
doi:10.1371/journal.pone.0064319.t002

Discussion

This is the largest European reference material of objectively measured aerobic capacity and exercise-physiology in healthy men and women aged 20–90 yrs. Our observations are an important supplement to previously published data that have mostly been either indirect or based on small, selected, or poorly-described populations [8–14].

Sex Differences in VO_{2max} and Maximal Heart Frequencies

Despite being generally more physical active than men, women had a 34% and 18.5% lower absolute (L·min⁻¹) and relative (mL·kg⁻¹·min⁻¹) VO_{2max}, respectively, than men. When applying

Table 3. O₂-pulse in the HUNT 3 Fitness study stratified by intensity levels, sex and age groups.

	Male			Female		
	Level 1	Level 2	Maximal	Level 1	Level 2	Maximal
20–29 years						
	(n = 121)	(n = 106)	(n = 199)	(n = 131)	(n = 111)	(n = 215)
O ₂ -pulse (mL·beat ⁻¹)	17.5±5.5	18.4±4.0	22.1±4.0	11.8±2.4	12.6±2.2	14.4±2.4
VO ₂ (mL·kg·min ⁻¹)	34.6±8.0	40.4±8.1	54.4±8.4	29.3±6.2	33.9±6.5	43.0±7.7
%VO _{2max}	63.7±12.3	72.7±10.6		68.1±11.0	76.6±9.6	
%f _{cmax}	80.7±8.8	87.8±5.4		85.0±8.3	90.7±6.4	
Workload (watts)	109±24	126±23	200±39	78±15	91±14	128±24
30–39 years						
	(n = 176)	(n = 166)	(n = 324)	(n = 247)	(n = 221)	(n = 359)
O ₂ -pulse (mL·beat ⁻¹)	17.5±2.9	18.3±2.9	22.3±3.6	12.2±2.5	12.9±2.6	14.7±2.7
VO ₂ (mL·kg·min ⁻¹)	29.8±5.5	34.2±5.7	49.1±7.7	27.2±5.3	31.0±5.5	40.0±6.8
%VO _{2max}	62.1±10.4	71.0±10.1		68.5±10.4	77.7±9.9	
%f _{cmax}	78.9±7.4	86.0±6.4		83.3±6.9	90.3±5.8	
Workload (watts)	110±21	124±20	197±33	77±16	91±18	128±23
40–49 years						
	(n = 351)	(n = 334)	(n = 526)	(n = 347)	(n = 320)	(n = 493)
O ₂ -pulse (mL·beat ⁻¹)	18.4±3.9	19.1±4.0	22.1±3.6	12.3±2.5	13.0±2.54	14.6±2.6
VO ₂ (mL·kg·min ⁻¹)	30.7±6.8	34.8±7.1	47.2±7.7	26.5±5.03	30.2±5.9	38.4±6.9
%VO _{2max}	65.1±10.6	73.7±10.4		70.1±10.4	79.0±9.8	
%f _{cmax}	78.6±7.7	85.7±7.3		83.1±7.1	90.0±6.0	
Workload (watts)	107±21	123±22	189±33	74±15	88±16	125±22
50–59 years						
	(n = 343)	(n = 314)	(n = 466)	(n = 354)	(n = 311)	(n = 428)
O ₂ -pulse (mL·beat ⁻¹)	17.8±3.3	18.5±3.3	20.7±3.6	11.8±2.1	12.3±2.2	13.4±2.2
VO ₂ (mL·kg·min ⁻¹)	28.5±6.0	32.1±6.1	42.6±7.4	24.1±4.0	27.1±4.3	34.4±5.7
%VO _{2max}	67.6±10.9	75.6±10.6		72.0±10.1	80.2±9.8	
%f _{cmax}	78.3±7.7	85.2±7.3		82.2±7.1	88.4±6.4	
Workload (watts)	99±20	117±21	173±28	67±17	79±18	117±23
60–69 years						
	(n = 258)	(n = 239)	(n = 300)	(n = 236)	(n = 204)	(n = 240)
O ₂ -pulse (mL·beat ⁻¹)	17.1±3.3	17.5±3.4	19.3±3.4	11.7±2.5	11.9±2.1	12.9±2.3
VO ₂ (mL·kg·min ⁻¹)	26.6±5.5	29.6±5.4	39.2±6.7	22.9±3.8	25.5±4.3	31.1±5.1
%VO _{2max}	66.4±11.0	76.5±11.0		74.8±9.9	81.9±9.2	
%f _{cmax}	77.9±8.5	84.6±8.0		83.8±8.4	89.3±7.4	
Workload (watts)	88±20	104±21	160±33	57±17	70±18	110±23
+70 years						
	(n = 95)	(n = 86)	(n = 76)	(n = 83)	(n = 71)	(n = 53)
O ₂ -pulse (mL·beat ⁻¹)	15.3±3.1	15.8±3.3	17.2±3.2	10.1±2.2	10.6±2.1	11.4±2.4
VO ₂ (mL·kg·min ⁻¹)	24.3±5.2	26.9±6.1	35.3±6.5	20.7±4.1	22.8±4.6	28.3±5.2
%VO _{2max}	70.7±10.9	77.8±11.0		74.5±10.4	81.8±9.0	
%f _{cmax}	80.9±7.7	86.2±8.0		84.2±7.2	90.0±7.7	
Workload (watts)	67±25	83±27	140±31	43±18	57±19	97±26

Data is presented as arithmetic mean ± SD. O₂-pulse: oxygen pulse, VO₂: oxygen uptake, %f_{cmax}: percent of maximum heart frequency, Workload: treadmill exercise load.

doi:10.1371/journal.pone.0064319.t003

appropriate scaling procedures [27] where differences in body mass are taken into consideration for a more accurate comparison [27–29], women had 22.7% lower VO_{2max} (mL·kg^{-0.75}·min⁻¹) than men. The higher VO_{2max} in men is in accordance with

former studies [5,10–14,30]. We observed higher VO_{2max} compared to that reported in American [9,11,13,14], Japanese populations [8] and a large Brazilian study [31], especially in the younger age groups. Earlier Scandinavian research supports our

Table 4. Relationships between perceived exertion, VO_{2max} and f_{cmax} in the HUNT 3 fitness study.

Borgscale	All			Male			Female		
	% f_{cmax}	95% CI	N	% f_{cmax}	95% CI	N	% f_{cmax}	95% CI	N
6–9	77.3	76.4–78.3	253	75.8	74.5–77.1	136	79.1	77.6–80.5	117
10–12	79.9	79.5–80.3	1475	78.1	77.6–78.6	813	82.2	81.6–82.7	662
13–15	86.6	86.3–86.7	3017	84.7	84.3–85.1	1459	88.4	88.0–88.7	1558
16–18	98.1	97.9–98.3	1775	98.1	97.8–98.4	862	98.2	97.9–98.5	913
19+	99.9	99.9–100	1216	99.9	99.7–100	560	100	99.98–100	656
Borgscale	% VO_{2max}			% VO_{2max}			% VO_{2max}		
	% VO_{2max}	95% CI	N	% VO_{2max}	95% CI	N	% VO_{2max}	95% CI	N
6–9	61.9	60.6–63.3	253	60.1	58.2–62.1	136	64.0	62.3–65.7	117
10–12	66.8	66.3–67.3	1475	64.7	64.1–65.4	813	69.3	68.6–70.0	662
13–15	76.7	76.3–77.1	3017	74.4	73.8–75.0	1459	78.8	78.3–79.4	1558
16–18	96.4	96.0–96.8	1775	96.5	96.0–97.1	862	96.3	95.8–96.8	913
19+	99.9	99.5–100	1216	99.8	99.5–100	560	99.9	99.9–100	656

Borgscale: subjective perception of perceived exertion (6–20), CI: confidence interval, % f_{cmax} : percent of maximal heart frequency, % VO_{2max} : percent of maximal oxygen uptake.

doi:10.1371/journal.pone.0064319.t004

VO_{2max} levels [25,32,33]. A study of Nomadic Lapps [34], who were physically active in taking care of their reindeers, observed VO_{2max} values close to our findings, and it is indicated that Roman legionnaires [35] had a VO_{2max} in the range of $50 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. Also contemporary hunter-gatherer societies display VO_{2max} in the range $50\text{--}65 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ in young male populations [36]. This supports the assumption that by living an active life, VO_{2max} in the range we display could be expected. When applying a scaled VO_{2max} [27], where differences in body weight is considered for a more precise comparison [27–29], the HUNT 3 fitness study still displays a considerable higher VO_{2max} ($\text{mL}\cdot\text{kg}^{-0.75}\cdot\text{min}^{-1}$) than North American, German and Asian studies. Scaled VO_{2max} in HUNT 3 was approximate 20% higher, considering both sexes and all age groups, than North American [9,10,37] and a German study [38]. However, a North American study by Jackson and colleagues [14] display only an estimated 10% lower scaled VO_{2max} , compared to our findings, among both sexes in the 20–29 year age group, with diminishing differences per subsequent decade. A Japanese study [8] displays an average 14% lower scaled VO_{2max} than us, among both sexes and all age groups. The dissimilarities between our and other findings may be explained by that we measured VO_{2max} whereas most others [8,9,11,14] use VO_{2peak} or estimated VO_{2max} [13,15], and that most other populations might also lead a more sedate lifestyle than that of Scandinavians.

Despite our relatively high mean VO_{2max} , 25 men and 9 women (>50 years) displayed values below 8 METs ($28 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and 6 METs ($21 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), respectively. This is associated with higher all-cause mortality and cardiovascular events among healthy men and women [4]. 1% of men 50–59 years displayed METs associated with increased risk, with 4% and 11% prevalence of “increased risk MET” with each subsequent decade. Women displayed approximately half the prevalence over the same age groups. We report a somewhat higher maximal heart rate than previous studies, which could be explained by that others [10–12] measure peak heart rate. In line with former studies [10–12] there were no significant sex differences in maximal heart rate.

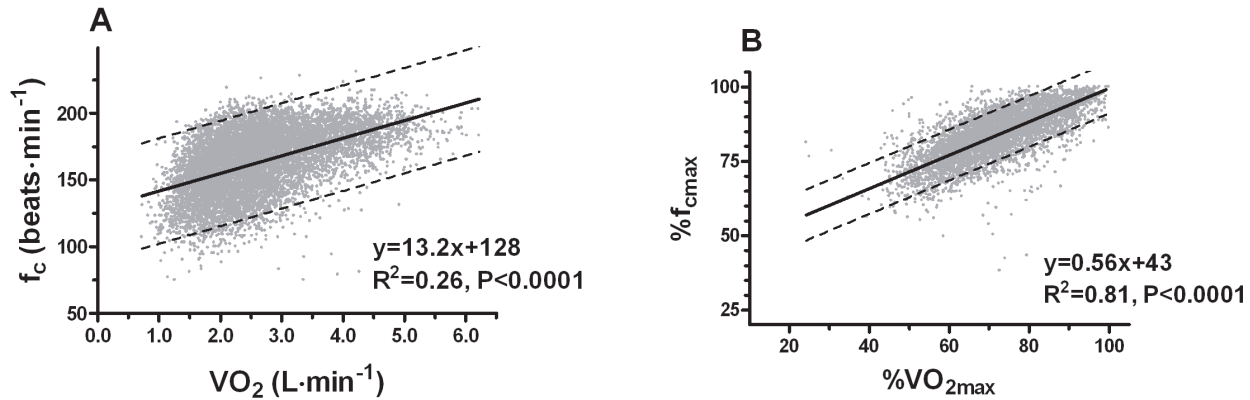
Differences in VO_{2max} and Physical Activity Level Stratified by Age Group and Sex

The highest VO_{2max} , in both men and women, were observed in the age groups 20–29 years. This fits with that both sexes in this age group had the highest level of physical activity compared to all other age groups. Between the two youngest age groups of both men and women (20–29 years and the 30–39 years) there was no difference in absolute VO_{2max} ($\text{L}\cdot\text{min}^{-1}$). However, among the 30–39 years old, body mass was 8.4% and 6.4% higher, and physical activity level 32.1% and 15.2% lower for men and women, respectively. A lower physical activity level did not influence the absolute VO_{2max} ($\text{L}\cdot\text{min}^{-1}$) but probably contribute to the higher body mass in those aged 30–39 years. Relative to body mass VO_{2max} ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) was 10% and a 7% lower among men and women aged 30–39 years compared to those in the 20–29 year age group. Thus, lower relative VO_{2max} in those aged 30–39 years old was caused by a higher body mass in our study population.

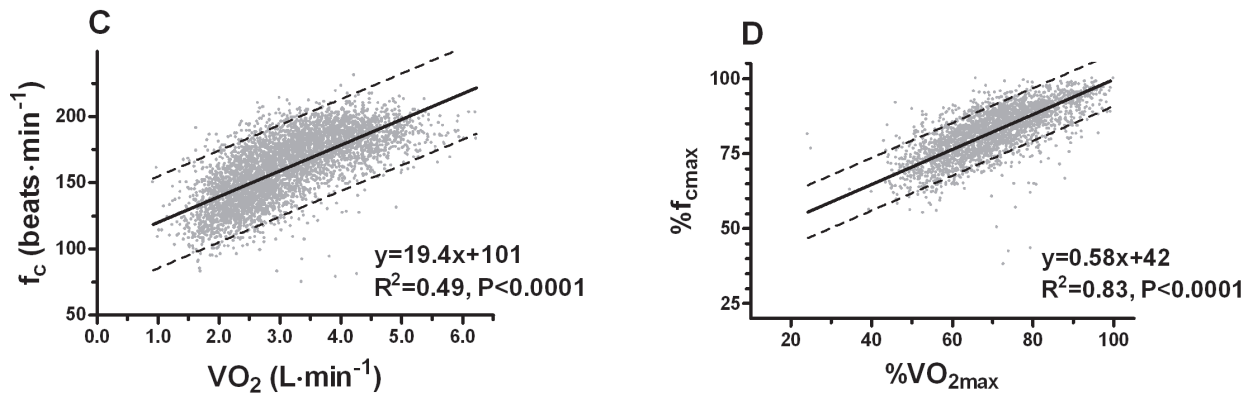
Despite similar body weights and physical activity level, a highly significant lower absolute (4.4%) and relative (3.8%) VO_{2max} was observed among men and women aged 40–49 years compared to those aged 30–39 years. In line with our findings, Sanada and colleagues [8] observed a similar drop in VO_{2max} between these age groups among healthy Japanese men. However, they observed a considerably larger “drop” in VO_{2max} with no change in body mass among women compared to our observations. Their findings are in agreement with another study of women by Jackson and colleagues [9]. A likely explanation for the lower VO_{2max} in those aged 40–49 vs. 30–39 could be a reduced level of physical activity in the oldest age group. However, our data does not support this. The Sanada [8] study shows a decrease in skeletal muscle mass with simultaneous increase in percent body fat. This would deteriorate demand properties and decrease VO_{2max} . We do not know if this is the case in our study, but the drop in absolute VO_{2max} yields a reduction in supply properties, hence a reduction in VO_{2max} . The reason for different “drop” in VO_{2max} among women in our study, the Sanada [8] and Jackson [9] studies is not known and warrant further studies.

Over the 3 next decades (40–69 years) the decrease in absolute and relative VO_{2max} had more than doubled ($\approx 10\%$ per decade),

ALL



MALE



FEMALE

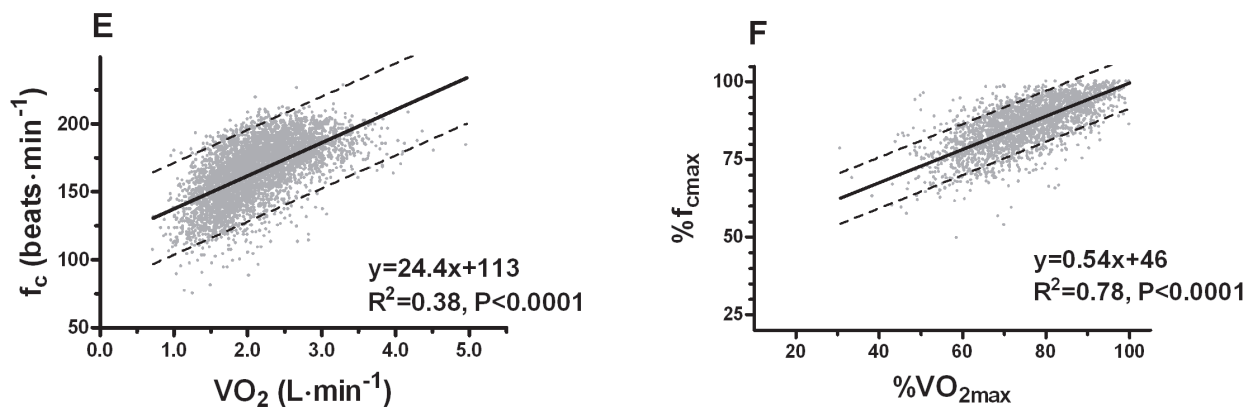
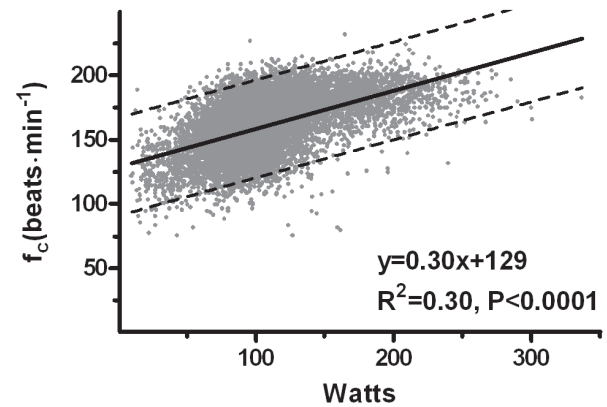
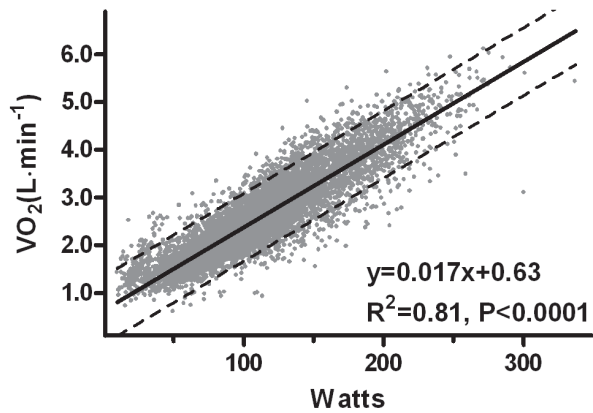


Figure 1. Correlations between oxygen uptake (VO_2) and heart rate (f_c).
doi:10.1371/journal.pone.0064319.g001

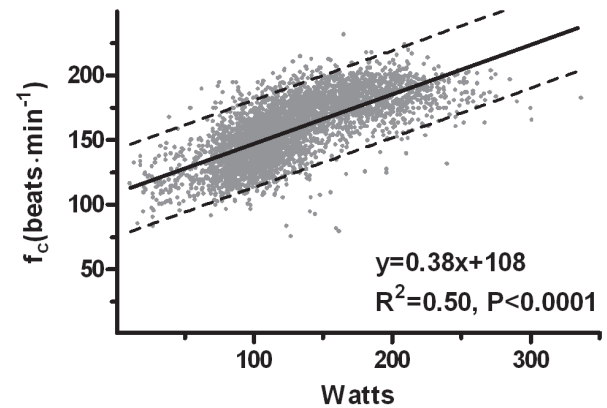
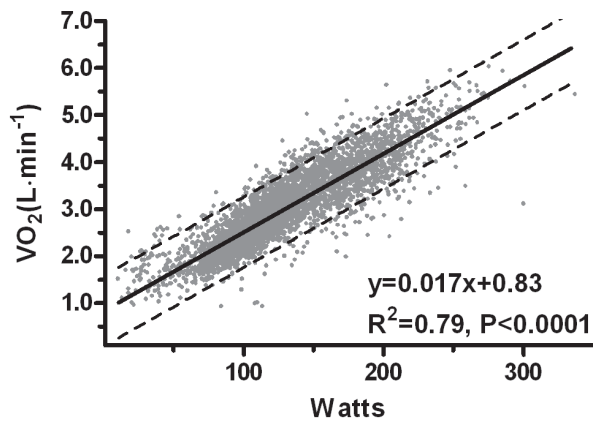
in both sexes, compared to that observed between age groups 30–39 years and 40–49 years. There were no significant differences in body mass between these age groups, with the exception of a $\approx 2\%$ reduction in males between 50–59 and 60–69 years. The reduction in VO_{2max} per decade is in line with previous studies

[8,11,14]. A significant reduction in physical activity level with increased age among women was observed in our study, with no changes in the male group. Thus, reduced physical activity level may explain reduced VO_{2max} with increased age among women but not among men. Whether this is really an age-related decline

ALL



MALE



FEMALE

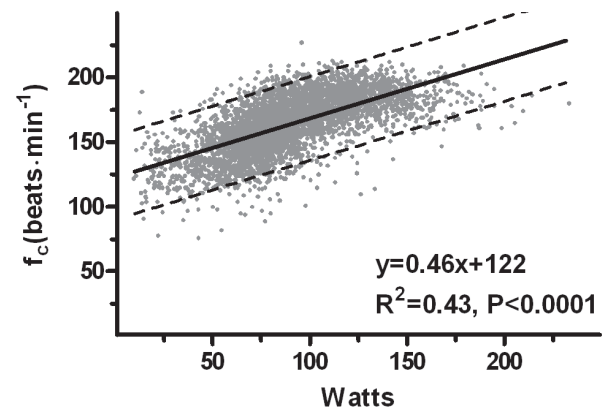
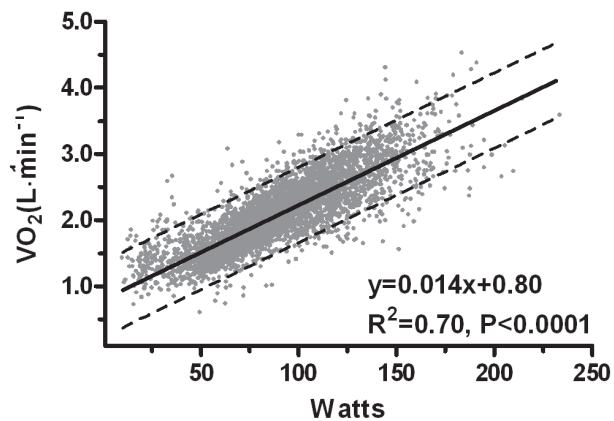


Figure 2. Correlations between workload (Watts) and oxygen uptake (VO_2) and correlations between Watts and heart rate (f_c).
doi:10.1371/journal.pone.0064319.g002

or due to that men have a tendency to over-report physical activity [39] is not known, and future investigations should aim to obtain objectively measured physical activity levels.

Between the 60–69 years and the +70 year age groups we observed the largest “drop” in absolute $VO_{2\text{max}}$ ($L \cdot \text{min}^{-1}$) in both sexes ($\approx 14.5\%$). Relatively $VO_{2\text{max}}$ ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) were 10%

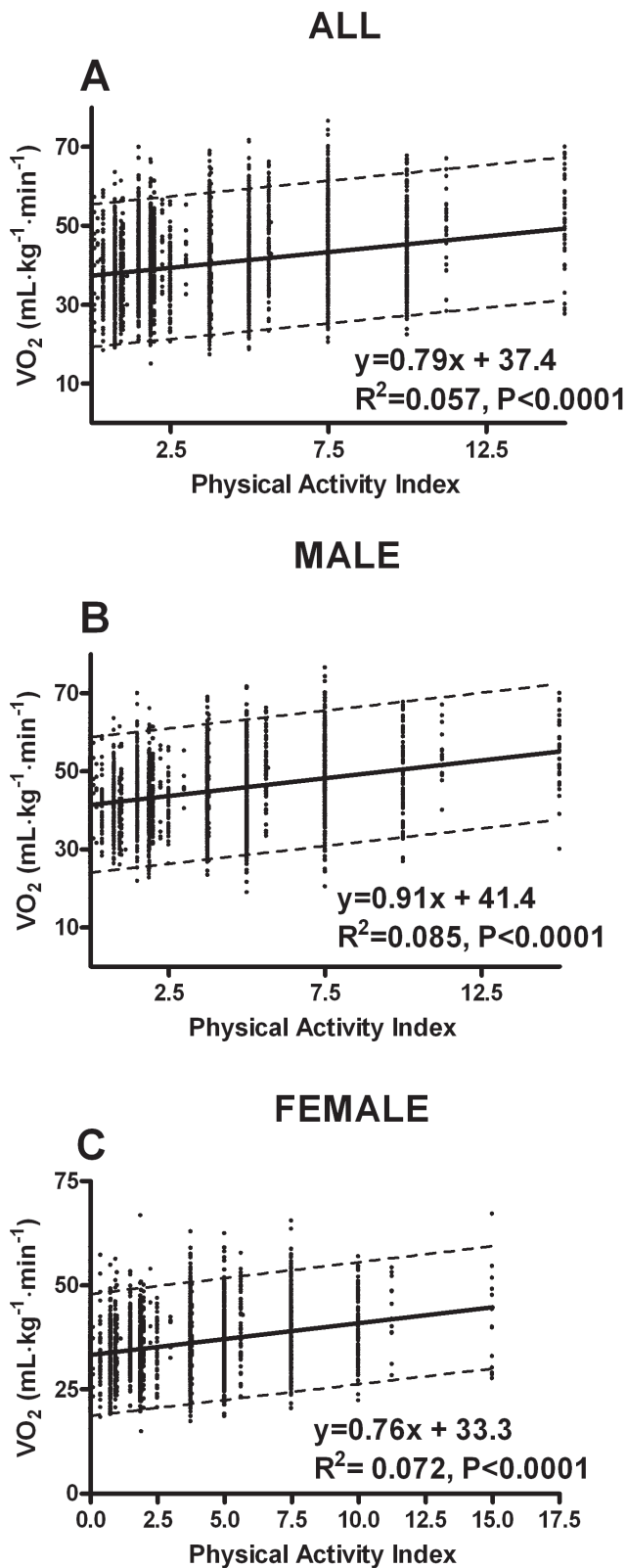


Figure 3. Correlations between physical activity index score and oxygen uptake (VO₂).
doi:10.1371/journal.pone.0064319.g003

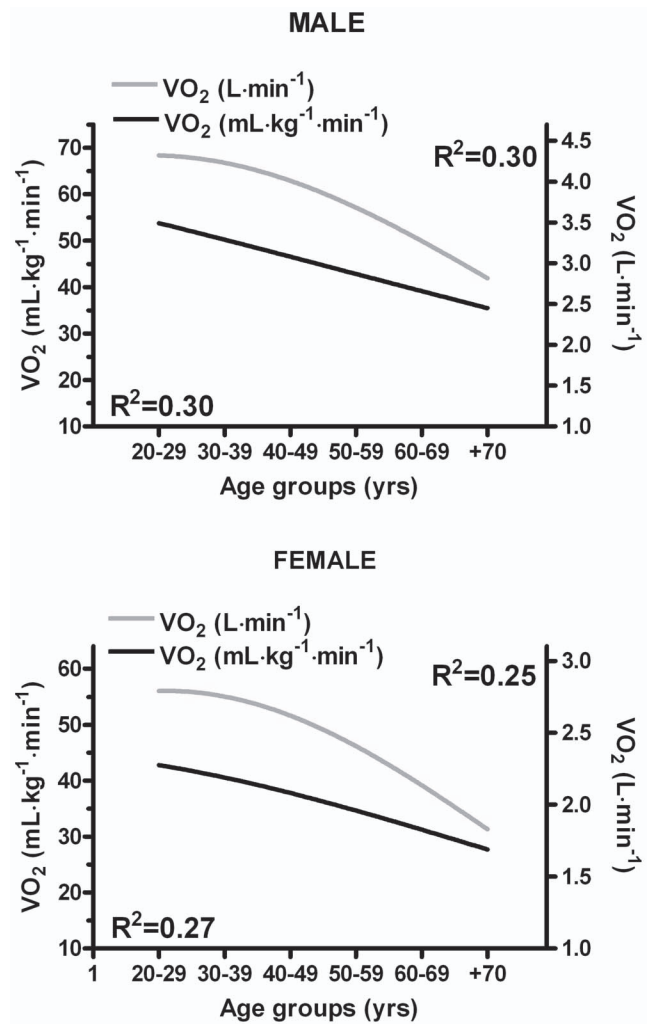


Figure 4. Decline of oxygen uptake (VO₂) relative to age. Mean and SD for each age group is presented in Table 2.
doi:10.1371/journal.pone.0064319.g004

and 11% lower in males and females aged +70 compared to those aged 60–69 years. The large drop in relative VO_{2max} occurred despite no significant drops in body mass and physical activity level. This suggests that the drop may be due to “age-related” adaptations in the organism. Our findings for these age groups are in line with previous studies reporting reductions in relative and absolute VO_{2max} in the range 13–25% and 12–29% [8,10,12,40].

Ventilatory efficiency, EqVO_{2max}, remains generally unchanged throughout the age groups; hence, it is not a factor in explaining the diminishing VO_{2max} with increasing age. However, subsequent 50 years of age O₂-pulse displayed a steady decrease, which indirectly indicate a reducing stroke volume, hence this yield a reduction in VO_{2max}.

Differences in Maximum Heart Rate Stratified by Age Group and Sex

Maximum heart rate has regularly been estimated by an equation subtracting age from 220 beats·min⁻¹, which have limited scientific merit [41]. The highest heart frequencies were found in the youngest age groups, regardless of sex. Maximal heart frequencies in men and women were 196±10 beats·min⁻¹ and 194±9 beats·min⁻¹, respectively, with a decline of approximately 3.5% (6 beats·min⁻¹) per decade. Our maximal heart rate decline

gradient is approximately half that compared to using the 220 beats·min⁻¹ minus age equation, which is consistent with former research [10,42,43].

Differences in Oxygen Pulse Stratified by Gender and Age Groups

The highest maximal oxygen pulse was observed in the 3 youngest age groups among men (22.3 ± 3.6 mL·beat⁻¹) and women (14.7 ± 2.7 mL·beat⁻¹), with no significant difference between these age groups. Previous reference material on oxygen pulse in healthy populations is based upon case reports [7] or small studies in athletes [44] [45] making comparison with our data complicated.

Association between VO₂ and Heart Rate

The benchmark studies of the relationship between submaximal VO₂ and heart frequencies from the 50's and 60's have small sample size. When comparing our findings with that of Åstrand [6] there are obvious discrepancies. Compared with our observations, Åstrand reports lower heart frequencies at workloads corresponding to VO₂ lower than 3 L·min⁻¹, and higher heart frequencies at VO₂ higher than 3 L·min⁻¹. Since there are no references to sample size or gender in Åstrand's data it is difficult to interpret the discrepancies between the studies. Another study by Åstrand [17] with 86 relatively well trained male and female students, agrees with our data, for the age group 20–29 years, on VO₂ less than 3 L·min⁻¹. When VO₂ exceed 3.0 L·min⁻¹ for females and 4.0 L·min⁻¹ for males the present study displays lower heart frequencies than reported in the Åstrand study. A study [18] with 44 females, aged 20–65 years, displayed lower heart frequencies than we observed for VO₂ < 1.5 L·min⁻¹, but higher heart frequencies for VO₂ > 1.5 L·min⁻¹. The observed association between percent VO_{2max} and percent maximal heart rate is in agreement with previous studies [16,18,19] on intensities > 70% of VO_{2max}. At exercise intensities < 70% of VO_{2max} we observed higher percent heart rate than previous studies. In our study 30% of VO_{2max} corresponded to 60% of maximal heart rate where others [16,18,19] have reported that this is equal to 50% of maximal heart rate. However, we use treadmill testing while the others use bicycle ergometer, which could explain the discrepancies.

Association between Heart Rate and Watts

Comparing our results to a study by Åstrand [20] with 84 healthy males, good agreement was found for workloads > 150W, whereas we observed progressively higher heart frequencies than Åstrand at lower workloads. This is also the case when comparing our results to another study of males by Åstrand [6]. Again, the inconsistency between our and Åstrand's findings could be explain by treadmill vs. bicycle ergometer.

Association between VO₂ and Watts

We systematically display higher VO₂ (L·min⁻¹) at any given watt than that observed in two studies from Åstrand [17,21]. Discrepancies seem to be caused by higher initial VO₂ cost (L·min⁻¹) in our results, while the slope gradient is in close proximity with Åstrand [17,21]. The differences may be explained by that we applied treadmill work whereas Åstrand used a cycle ergometer.

Association between Borg Scale Scores, % VO_{2max} and % Maximal Heart rRate

We observed a mismatch between the Borg study [22] and our findings. We observed considerably higher percent VO_{2max} and

percent maximal heart rate for a given exertion interval than Borg [22], but differences vanished at the highest Borg-levels.

Relative to VO_{2max} and maximal heart rate Borg scale differed between sexes. In the range 6–15 on Borg scale males worked at a lower percent (4%) of both VO_{2max} and maximal heart rate than females, i.e. the relative rating of perceived exertion in males were higher at a given work load. There were no differences between sexes at Borg 16–20. Our data clearly support the notion that Borg-scale may be used as a robust tool to guide exercise intensity in healthy men and women, but that one should be aware of sex differences at the lowest Borg levels.

Association between Physical Activity Index Scores and VO_{2max}

There was a poor overall correlation ($r = 0.24$) between self-reported physical activity level and VO₂, which indicates that only 5.7% of differences in VO_{2max} can be explained by the physical activity scores. This is in agreement with prior research [11,46,47]. Physical activity index score (PAI) is a weighted product between duration, frequency and intensity. Intensity might be weighted to low, thus it could explain the poor correlation between PAI and VO₂.

Limitations

This study may be subject to bias due to self-selection caused by the low participation rate. However, almost all of those who were invited to the current Fitness study from the large HUNT study agreed to participate in the fitness test. Due to limited capacity at the test sites resulting in long waiting lines, many potential participants chose to withdraw their participation from the study. Those who finally participated in the study could thus be healthier than those who quit or declined participation. However, a comparison of the participants in the fitness study with a healthy sample of the total HUNT population (i.e. free from cardiovascular or pulmonary diseases, cancer, or sarcoidosis) confirmed that the fitness participants did not considerably differ from other healthy HUNT participants [48]. In future studies physical activity should be measured objectively rather than being self-reported, given the large inconsistencies between VO_{2max} and self-reported physical activity.

Conclusions

The discrepancies between this and previous studies highlighted the need of a large reference material as presented in this study. The HUNT 3 Fitness study presents the largest European reference material of objectively measured parameters of aerobic capacity and exercise-physiology in healthy men and women aged 20–90 years. Our data establishes normal values for the key physiological factors VO_{2max} and heart rate, as well as associations between commonly used exercise parameters. The data forms the basis for a user-friendly tool for exercise intensity control in healthy men and women.

Acknowledgments

The HUNT 3 fitness study is a collaboration between The HUNT research center (Faculty of Medicine, Norwegian University of Science and Technology, NTNU), Nord-Trøndelag County Council and The Norwegian Institute of public Health, Liaison Committee between the Central Norway Regional Health Authority (RHA) and the Norwegian University of Science and Technology (NTNU).

Author Contributions

Conceived and designed the experiments: UW. Performed the experiments: UW OR. Analyzed the data: HL OR BS UW. Contributed reagents/materials/analysis tools: HL OR BS UW. Wrote the paper: HL

References

- Erikssen G, Liestol K, Bjornholt J, Thaulow E, Sandvik L, et al. (1998) Changes in physical fitness and changes in mortality. *Lancet* 352: 759–762.
- Myers J, Prakash M, Froelicher V, Do D, Partington S, et al. (2002) Exercise capacity and mortality among men referred for exercise testing. *N Engl J Med* 346: 793–801.
- Sandvik L, Erikssen J, Thaulow E, Erikssen G, Mundal R, et al. (1993) Physical fitness as a predictor of mortality among healthy, middle-aged Norwegian men. *N Engl J Med* 328: 533–537.
- Kodama S, Saito K, Tanaka S, Maki M, Yachi Y, et al. (2009) Cardiorespiratory fitness as a quantitative predictor of all-cause mortality and cardiovascular events in healthy men and women: a meta-analysis. *JAMA* 301: 2024–2035.
- Lee DC, Sui X, Ortega FB, Kim YS, Church TS, et al. (2011) Comparisons of leisure-time physical activity and cardiorespiratory fitness as predictors of all-cause mortality in men and women. *Br J Sports Med* 45: 504–510.
- Åstrand P, Rodahl K, Dahl H, Strømme S (2003) *Textbook of Work Physiology Physiological Bases of Exercise*: McGraw-Hill.
- Wasserman K, Hansen JE, Sue DY, Stringer WS, Sietsema KE, et al. (2012) *Principles of Exercise Testing and Interpretation*: Lippincott Williams & Wilkins.
- Sanada K, Kuchiki T, Miyachi M, McGrath K, Higuchi M, et al. (2007) Effects of age on ventilatory threshold and peak oxygen uptake normalised for regional skeletal muscle mass in Japanese men and women aged 20–80 years. *Eur J Appl Physiol* 99: 475–483.
- Jackson AS, Wier LT, Ayers GW, Beard EF, Stuteville JE, et al. (1996) Changes in aerobic power of women, ages 20–64 yr. *Med Sci Sports Exerc* 28: 884–891.
- Fleg JL, Morrell CH, Bos AG, Brant IJ, Talbot LA, et al. (2005) Accelerated longitudinal decline of aerobic capacity in healthy older adults. *Circulation* 112: 674–682.
- Talbot LA, Metter EJ, Fleg JL (2000) Leisure-time physical activities and their relationship to cardiorespiratory fitness in healthy men and women 18–95 years old. *Med Sci Sports Exerc* 32: 417–425.
- Hollenberg M, Ngo LH, Turner D, Tager IB (1998) Treadmill exercise testing in an epidemiologic study of elderly subjects. *J Gerontol A Biol Sci Med Sci* 53: B259–267.
- Wang CY, Haskell WL, Farrell SW, Lamonte MJ, Blair SN, et al. (2010) Cardiorespiratory fitness levels among US adults 20–49 years of age: findings from the 1999–2004 National Health and Nutrition Examination Survey. *Am J Epidemiol* 171: 426–435.
- Jackson AS, Sui X, Hebert JR, Church TS, Blair SN (2009) Role of lifestyle and aging on the longitudinal change in cardiorespiratory fitness. *Arch Intern Med* 169: 1781–1787.
- Armstrong L, Balady GJ, Berry MJ, Davis SE, Davy BM, et al. (2006) *ACSM's Guidelines for Exercise Testing and Prescription*: Lippincott Williams & Wilkins. 79 p.
- McArdle W, Katch F, Katch V (2010) *Exercise Physiology, Nutrition, Energy, and Human Performance*. Philadelphia, PA: Lippincott Williams & Wilkins.
- Åstrand P (1952) Experimental studies of physical working capacity in relation to sex and age. Copenhagen: Munksgaard.
- Taylor H, Haskell W, Fox S, Blackburn H (1969) *Measurement in Exercise Electrocardiography*; Blackburn H, editor. Illinois, USA: Charles C Thomas Publisher.
- Pollock M, Wilmore J, Fox S (1978) *Health and fitness through physical activity*: John Wiley & Sons.
- Astrand I (1967) Degree of strain during building work as related to individual aerobic work capacity. *Ergonomics* 10: 293–303.
- Astrand PO (1976) Quantification of exercise capability and evaluation of physical capacity in man. *Prog Cardiovasc Dis* 19: 51–67.
- Borg GA (1982) Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 14: 377–381.
- Alberton CL, Antunes AH, Pinto SS, Tartaruga MP, Silva EM, et al. (2011) Correlation between rating of perceived exertion and physiological variables during the execution of stationary running in water at different cadences. *J Strength Cond Res* 25: 155–162.
- Rognmo O, Hetland E, Helgerud J, Hoff J, Slordahl SA (2004) High intensity aerobic interval exercise is superior to moderate intensity exercise for increasing aerobic capacity in patients with coronary artery disease. *Eur J Cardiovasc Prev Rehabil* 11: 216–222.
- Hermansen L, Saltin B (1969) Oxygen uptake during maximal treadmill and bicycle exercise. *J Appl Physiol* 26: 31–37.
- Kurtze N, Rangul V, Hustvedt BE, Flanders WD (2008) Reliability and validity of self-reported physical activity in the Nord-Trøndelag Health Study: HUNT 1. *Scand J Public Health* 36: 52–61.
- Batterham AM, Birch KM (1996) Allometry of anaerobic performance: a gender comparison. *Can J Appl Physiol* 21: 48–62.
- Chamari K, Moussa-Chamari I, Boussaidi L, Hachana Y, Kaouech F, et al. (2005) Appropriate interpretation of aerobic capacity: allometric scaling in adult and young soccer players. *Br J Sports Med* 39: 97–101.
- Helgerud J (1994) Maximal oxygen uptake, anaerobic threshold and running economy in women and men with similar performances level in marathons. *Eur J Appl Physiol Occup Physiol* 68: 155–161.
- Macek M, Seliger V, Vavra J, Skranc O, Horak J, et al. (1979) Physical fitness of the Czechoslovak population between the ages of 12 and 55 years. Oxygen consumption and pulse oxygen. *Physiol Bohemoslov* 28: 75–82.
- Herdy AH, Uhlendorf D (2011) Reference values for cardiopulmonary exercise testing for sedentary and active men and women. *Arq Bras Cardiol* 96: 54–59.
- Hermansen L, Andersen KL (1965) Aerobic work capacity in young Norwegian men and women. *J Appl Physiol* 20: 425–431.
- Andersen LB, Henckel P, Saltin B (1987) Maximal oxygen uptake in Danish adolescents 16–19 years of age. *Eur J Appl Physiol Occup Physiol* 56: 74–82.
- Lange-Andersen L, Elsner R, Saltin B, Hermansen L (1961–1962) Physical fitness in terms of maximal oxygen uptake of nomadic lapps. Arctic Aeromedical Laboratory, Alaska.
- Mitchell JH, Saltin B (2003) *The oxygen transport system and maximal oxygen uptake*. New York: Oxford University press.
- Cordain L, Gotshall RW, Eaton SB, Eaton SB 3rd (1998) Physical activity, energy expenditure and fitness: an evolutionary perspective. *Int J Sports Med* 19: 328–335.
- Nelson MD, Petersen SR, Dlin RA (2010) Effects of age and counseling on the cardiorespiratory response to graded exercise. *Med Sci Sports Exerc* 42: 255–264.
- Meyer K, Hajric R, Samek L, Baier M, Lauber P, et al. (1994) Cardiorespiratory exercise capacity in healthy normals of different age. *Cardiology* 85: 341–351.
- Klesges RC, Eck LH, Mellon MW, Fullilton W, Simes GW, et al. (1990) The accuracy of self-reports of physical activity. *Med Sci Sports Exerc* 22: 690–697.
- Weiss EP, Spina RJ, Holloszy JO, Ehsani AA (2006) Gender differences in the decline in aerobic capacity and its physiological determinants during the later decades of life. *J Appl Physiol* 101: 938–944.
- Robergs R, Landwehr R (2002) The surprising history of the “HRmax = 220-age” Equation. *Journal of Exercise Physiology* online 5.
- Tanaka H, Monahan KD, Seals DR (2001) Age-predicted maximal heart rate revisited. *J Am Coll Cardiol* 37: 153–156.
- Gellish RL, Goslin BR, Olson RE, McDonald A, Russi GD, et al. (2007) Longitudinal modeling of the relationship between age and maximal heart rate. *Med Sci Sports Exerc* 39: 822–829.
- Sharma S, Elliott PM, Whyte G, Mahon N, Virdee MS, et al. (2000) Utility of metabolic exercise testing in distinguishing hypertrophic cardiomyopathy from physiologic left ventricular hypertrophy in athletes. *J Am Coll Cardiol* 36: 864–870.
- Padilla P, Ojeda C, Fernandez C, Licea M (2000) Maximum oxygen pulse in high performance mexican athletes. *Rev Inst Nal Enf Resp Mex* 13: 73–84.
- van Poppel MN, Chinapaw MJ, Mokkink LB, van Mechelen W, Terwee CB (2010) Physical activity questionnaires for adults: a systematic review of measurement properties. *Sports Med* 40: 565–600.
- Tager IB, Hollenberg M, Satariano WA (1998) Association between self-reported leisure-time physical activity and measures of cardiorespiratory fitness in an elderly population. *Am J Epidemiol* 147: 921–931.
- Aspenes ST, Nilsen TI, Skaug EA, Bertheussen GF, Ellingsen O, et al. (2011) Peak oxygen uptake and cardiovascular risk factors in 4631 healthy women and men. *Med Sci Sports Exerc* 43: 1465–1473.