Published January 25, 2019

VO_2 Max Computed from Wearable Devices using only GPS and Accelerometer data

Myotest SA

Abstract
This white paper describes a study assessing the accuracy of the Myotest software solution to estimate VO_2 Max against a Gold Standard. Myotest solution uses GPS and accelerometer sensors only and does not require a heart rate sensor.

Keywords
VO_2 Max, Accelerometer, Ergospirometry, Running

Contents

Summary

- VO_2 Max measurements are essential for runners to help them track aerobic fitness level and progress through training.
- Current solutions for measuring VO_2 Max in the field are based on heart rate sensors available in wearable devices with a mean absolute error of 5-8% [1].
- Myotest novel method to compute VO_2 Max is based on biomechanics and does not require a heart rate sensor. It is measured from a watch during a 15 min dedicated running protocol based only on GPS and accelerometer data. The later is used to compute key biomechanical running metrics.
- This study has been realised with 85 runners using portable ergospirometer Cosmed K5 and VAMEVAL protocols as Gold Standard.
- Myotest measures VO_2 Max with a 6% mean absolute error rate, similar to the accuracy of solutions using heart rate sensor data.

Introduction

VO_2 Max is one of the most important predictor for endurance performance as it represents the maximum capacity of an individual's body to transport and use oxygen during exercising. It summarizes the physical fitness of any individual in a simple number. Tracking VO_2 Max and its changes is beneficial to quantify the training progress, to predict future performances and to assess potential adverse health effects regarding treatment outcomes. Typically VO_2 Max is measured either in a lab with a complex set of sensors or is estimated using heart rate sensors from consumer wearable devices. Myotest has developed a novel software solution to estimate VO_2 Max using only the GPS and accelerometer embedded in consumer wearables like smartwatches, headsets or smartphones. Myotest algorithms use the accelerometer data to compute key biomechanical metrics while running. The aim of this paper is to discuss the accuracy of Myotest's VO_2 Max compared to a Gold Standard.

VO_2 Max Background

Definition

Maximal volume of oxygen uptake, or VO_2 Max, is defined as the maximum ability of an individual to capture oxygen, transport it and use it at the muscular level. It is normally measured in liters per minute [L/min] but as to allow comparison between individuals, we tend to express it in milliliters of oxygen per kilogram per minute [ml/kg/min] [2]. VO_2 Max is influenced by a person's genetics and training regimen. Norms of VO_2 Max have been defined based on age and gender [2] to assess fitness levels (see Tables 1 and 2) .

Importance of VO_2 Max

VO_2 Max is widely used in sports and medical context as a metric related to aerobic fitness, performance and cardiovascular health [3]. There are many reasons to use VO_2 Max in training:

Table 1. Maximal oxygen uptake norms for men (ml/kg/min).

	Age					
Rating	**18 - 25**	**26 - 35**	**36 - 45**	**46 - 55**	**56 - 65**	**65+**
Excellent	>60	>56	>51	>45	>41	>37
Good	52-60	49-56	43-51	39-45	36-41	33-37
Above Average	47-51	43-48	39-42	36-38	32-35	29-32
Average	42-46	40-42	35-38	32-35	30-31	26-28
Below Average	37-41	35-39	31-34	29-31	26-29	22-25
Poor	30-36	30-34	26-30	25-28	22-25	20-21
Very Poor	<30	<30	<26	<25	<22	<20

Table 2. Maximal oxygen uptake norms for women (ml/kg/min).

	Age					
Rating	**18 - 25**	**26 - 35**	**36 - 45**	**46 - 55**	**56 - 65**	**65+**
Excellent	>56	>52	>45	>40	>37	>32
Good	47-56	45-52	38-45	34-40	32-37	28-32
Above Average	42-46	39-44	34-37	31-33	28-31	25-27
Average	38-41	35-38	31-33	28-30	25-27	22-24
Below Average	33-37	31-34	27-30	25-27	22-24	19-21
Poor	28-32	26-30	22-26	20-24	18-21	17-18
Very Poor	<28	<26	<22	<20	<18	<17

Monitor Fitness Level and Training Effect

Runners can efficiently assess their fitness level and track their progress by looking at their VO_2 Max and its change over time. As discussed in [4], "VO_2 Max is frequently used to indicate the cardiorespiratory fitness of an individual" and an increase in VO_2 Max is "the most common method of demonstrating a training effect" [4]. Of course genetics has a great impact on the initial value of VO_2 Max and by how much it may change [5], nevertheless everybody can increase their VO_2 Max through proper training. Different training modalities (volume, intensity) are affecting differently the increase [6] [7] as seen in figure 1.

Predict Race Time

VO_2 Max is a great indicator to predict individuals race time. The extensive use of VO_2 Max in research and sports has supported the creation of tables to predict the finish time for a given distance considering VO_2 Max level. They are also great indicators for beginners willing to take part to a competitive run to assess their race time.

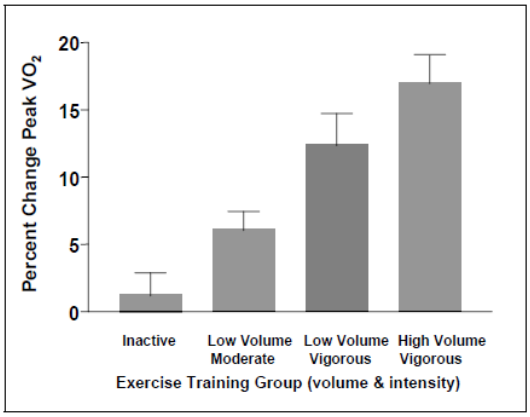

Figure 1. VO_2 Max change in several groups following different exercise modalities (volume, intensity) [6].

Figure 2. Performance test using ergospirometry on a treadmill.

Manage Training Loads and Specific Training

The ability to easily measure VO_2 Max in the field [8] [9] [10] has democratized its use by coaches in sport to customize and personalize the design and modification of training plans. Training plan intensity and volume are adjusted by taking into account VO_2 Max value and its changes. It is also possible to train at specific percentages of your VO_2 Max in order to elicit desired adaptations through training (anaerobic vs aerobic, recovery,...).

The Gold Standard for VO_2 Max

Spirometry is recognized as the Gold Standard for measurements on ventilation and energy expenditure. Most of the tests involving spirometry require the subject to exercise either on a bicycle ergometer or on a treadmill until reaching a maximum level of exhaustion. "A breathing mask collects some of the air you inhale and exhale for respiratory analysis with each breath. This enables accurate determination of the volumes of oxygen uptake (VO_2) and carbon dioxide output (VCO_2)" [11]. These allow the precise calculation of maximum oxygen uptake that is characterized by a plateau in oxygen uptake although the intensity keeps increasing. You can see an example of such a performance test in figure 2[1]. According to industry standards, "the VO_2 Max measurement error in a typical indirect submaximal test is about 10-15% and in a direct laboratory test about 5%" [1]. A low error rate is definitely desirable however consistency in estimating VO_2 Max is key. An increase in VO2 Max should be only related to an improvement in aerobic fitness and not to a measurement error.

VO_2 Max Estimate Using Biomechanics

Myotest is a leading supplier of software solutions to measure biomechanical parameters in sport & health from any wearable device. Myotest's solution is location-agnostic and works equally well from a watch, a smartphone in the hand or a device at the upper arm, a Chest Strap or a pod on the

[1] source: https://korr.com/products/vo2-max-testing-system/

waist belt. Myotest's core biomechanical features for running include running power, vertical oscillation, contact time, flight time, stiffness, asymmetry, regularity, reactivity. See www.myotest.com/core-features for the full list and details.

The Use of Biomechanics to Track Performance and VO_2 Max Progress

Table 3. VO_2 Max values and marathon personal records of famous runners.

Runner	VO_2 Max	Marathon P.R.
Bill Rodgers	78.5	2:09:27
Don Kardong	77.4	2:11:15
Alberto Salazar	76.0	2:08:51
Johnny Halberstadt	74.4	2:11:44
Kenny Moore	74.2	2:11:36
Zithulele Singe	72.0	2:08:05
Willie Mtolo	70.3	2:08:15
Derek Clayton	69.7	2:08:35

When looking at Table 3[2], it is striking to notice that Derek Clayton has a better marathon P.R. than Bill Rodgers despite a significant difference in their VO_2 Max values. This demonstrates that although VO_2 Max values are important for endurance, there are other VO_2 Max-related metrics that play a role in performance such as time sustainable at VO_2 Max as described by Billat et al., "the minimal velocity which elicits VO_2 Max and the tlim at this velocity appear to convey valuable information when analysing a runner's performance" [12]. Being able to optimise those metrics is highly correlated to the efficiency of a runner's biomechanics. Thus by training biomechanics runners are able to increase their performance level and optimise their oxygen consumption.

Myotest Solution to Measure VO_2 Max

To calculate VO_2 Max, Myotest has defined a specific protocol based on the runner speed (using the GPS) and relevant biomechanical parameters. This protocol is based on a 3x5 minutes interval as described below and was designed by taking into account research on different field protocols [13]. This protocol consists of running successfully five minutes three times set as follows:

1. Run for 5 minutes at a self-selected warm-up pace.
2. Run for 5 minutes at a self-selected casual pace. The pace at which the runner is the most comfortable at running.
3. Run for 5 minutes at a self-selected maximal pace. The aim is to run as fast as possible however it is also to maintain a regularity as high as possible while running. Starting too fast and not being able to hold out until the end has to be avoided at all cost.

[2]source: https://www.marathonnation.us/pace/run-fitness-is-in-your-running-muscles/

Figure 3. VAMEVAL protocol setup.

Runners performing the protocol are required to wear either a watch or a smartphone with Myotest software. Myotest's software is designed to use the GPS available in the wearable for speed calculation and the accelerometer to calculate key biomechanical parameters of the runner.

Study Methodology

Myotest conducted a study with 85 subjects (See Table 4) to validate the accuracy of VO_2 Max estimates against Gold Standard.

Table 4. Population characteristics.

Population	85 runners (58 men, 27 women)
Age ($mean \pm std$)	$36 \pm 9 years$
Height ($mean \pm std$)	$1.73 \pm 0.08 m$
Weight ($mean \pm std$)	$67.9 \pm 9.5 kg$
MAV Reference ($mean \pm std$)	$15.8 \pm 2.07 km/h$
VO_2 Max Reference ($mean \pm std$)	$54.7 \pm 8.1 ml/kg/min$

Methodology

In this study, all subjects underwent two tests. One was to run the Myotest protocol defined above and the second test was to calculate the Gold Standard using a VAMEVAL[3] outdoor test, following standard procedure (see figure 3). The VO_2 Max data was calculated with the help of a portable ergospirometer (Cosmed K5) by measuring the VO_2 during the entire test. The VO_2 Max was determined as the average VO_2 for the last completed stage of the test.

[3]VAMEVAL is a popular incremental field test to estimate VO_2 Max.

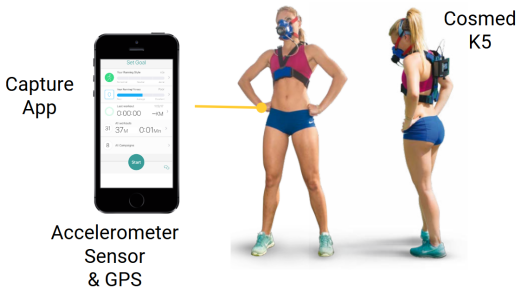

Figure 4. Each subjects was wearing 2 devices: an iPhone in the right hand and K5 Cosmed ergospirometer on the back.

Runner Setup

Each subject was equipped with a total of one device using Myotest's software (iPhone) as well as the K5 Cosmed portable ergospirometer (see figure 4). The Cosmed K5 allows portable spiroergometry, heart rate as well as GPS recordings. It is worn on the back and weighs less than 1 kg. The iPhone was in the right hand. All the accelerometer and GPS data were recorded by the Myotest software running on the iPhone (see figure 4).

Data Collection Protocol

The data capture took place on an athletic outdoor track. Age, gender, height and weight were entered in each device to allow the respective software to adjust to the anthropometric data. A calibration of the ergospirometry was executed to match outside temperature, pressure and humidity conditions before each measurement. All runners performed the Myotest dedicated protocol first and the VAMEVAL test during another training session. The VAMEVAL test was recorded using the same sensor setup as for the Myotest protocol with adding additionally Cosmed's K5 ergospirometry. This protocol was developed to simplify and increase the precision of the Léger & Boucher test whose accuracy and reliability in estimating VO_2 Max in outdoor conditions is validated against lab protocols [14]. It follows a triangular continuous protocol [15]. Here is the description of the VAMEVAL protocol:

- Each runner starts at a speed ranging from 7 to 12 km/h.
- Cones are placed every 20 meters around the track.
- The runner is guided by an audio signal "Bip" through the protocol, i.e. the runner has to reach the next cone at the next bip.
- Progressive increase of speed (0,5 km/h every minute) using the audio signal as an indicator.
- Determination of the time point, at which the runner cannot follow the rhythm anymore. The last completed stage allows to calculate the maximum aerobic velocity (MAV) and the VO_2 Max.

Results

We compared Myotest VO_2 Max based on the 3x5 minutes protocol to the Gold Standard measured average VO_2 by the Cosmed K5 spirometer. This section presents the error rate of Myotest VO_2 Max compared to Gold Standard using two different methods: the mean absolute error rate and a Bland-Altman graph.

The Mean Absolute Error Rate

Compared to the Gold Standard, the Myotest VO_2 Max shows a mean absolute error rate of $6.0\% \pm 4.5\%$.

The Bland-Altman Graph

The Bland-Altman graphs in figure 5 shows that the error is evenly distributed. The systematic bias is very low (MEAN = 0.83; STD = 3.97). The 95% limits of agreement show that the differences between Myotest and Gold Standard measurements are below 8 [ml/kg/min].

Conclusion

This study has shown that Myotest VO_2 Max has a mean absolute error rate of 6.0% compared to a Gold Standard measured with the VAMEVAL protocol and ergospirometry. This accuracy value is remarkably close to the ones that are calculated by using heart rate sensors on wearable devices [1]. In addition, the Bland-Altman graph shows evidence that Myotest VO_2 Max is estimated reliably as demonstrated by the very low systematic bias and the fairly symmetric 95% limits

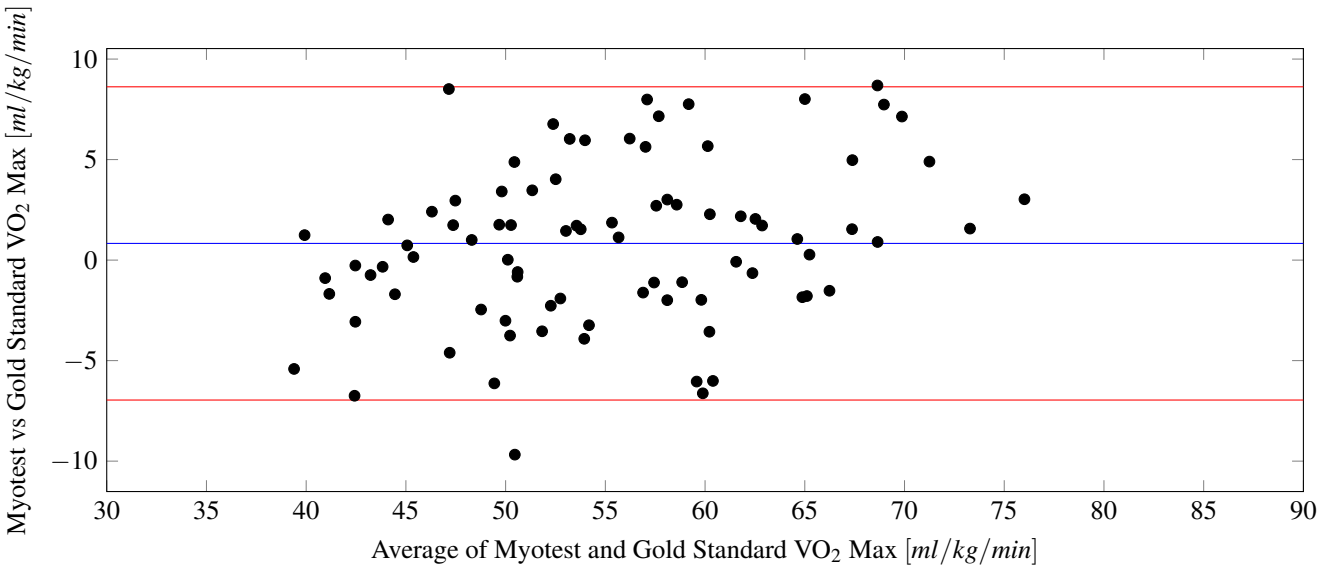

Figure 5. Bland-Altman graph for Myotest VO2 Max estimation against Gold Standard. The mean is in blue and the 95% limits of agreement in red.

of agreement. Myotest solution gives an accurate estimate of VO_2 Max and only requires a GPS and an accelerometer signal to calculate key biomechanical parameters. It does require a 15 minutes running protocol for each assessment, however there is no need for a heart rate measurement device.

About Myotest

Myotest believes that sports - running in particular - should remain accessible, simple and safe. Myotest delivers smart software and services for wearable devices to help athletes achieve their goals confidently, improve their efficiency, and reduce the risk of injury. Wearable device manufacturers and app developers license Myotest software and services for their next-generation products. Founded in 2004, the company is a pioneer in the capture, analysis and interpretation of biomechanical metrics. The Myotest system has been used by over 20,000 professionals in sports and health. The Myotest patent portfolio includes more than 50 issued and pending patents. Learn more at `www.myotest.com`.

References

[1] Firstbeat Technologies Ltd. Automated fitness level (vo2 max) estimation with heart rate and speed data. 2014.

[2] David Costill W. Larry Kenney, Jack Wilmore. *Physiology of Sport and Exercise 6th Edition*. Human Kinetics, 2015.

[3] Blair S. N. et al. Influences of cardiorespiratory fitness and other precursors on cardiovascular disease and all-cause mortality in men and women. 1996.

[4] Bassett & Howley. Limiting factors for maximum oxygen uptake and determinants of endurance performance. 2000.

[5] M. R. Boulay C. Bouchard. Genetics of aerobic and anaerobic performance. 1992.

[6] Duscha B. D. et al. Effects of exercise training amount and intensity on peak oxygen consumption in middle-age men and women at risk for cardiovascular disease. 2005.

[7] T. Rankinen C. Bouchard. Individual differences in response to regular physical activity. 2001.

[8] Philip D. Campagna John A. Grant. The prediction of vo2 max: A comparison of 7 indirect tests of aerobic power. 1999.

[9] K. Mendes de Souza et al. Performance prediction of endurance runners through laboratory and track tests. 2014.

[10] D. Mercier L. Léger. Coût énergétique de la course sur tapis roulant et sur piste. 1983.

[11] sportclinic. sportclinic. `http://www.sportclinic.ch`, 2019. Accessed: 2019-01-15.

[12] J. P. Koralsztein V. L. Billat. Significance of the velocity at vo2 max and time to exhaustion at this velocity. 1996.

[13] J-F. Laubignat A. Chamoux, P. Berthon. Determination of maximum aerobic velocity by a five minute test with reference to running world records. a theoretical approach. 1996.

[14] R. Boucher L. Léger. An indirect continuous running multistage field test: the university de montréal track test. 1980.

[15] Georges Cazorla. Evaluation des capacités physiologiques et physiques - evaluation des capacités aérobies. 2014.