

Analysis of Health and Fitness Benefits of Physical Activity Based on Heart Rate Measurements

Firstbeat Technologies Ltd.

This white paper has been produced to describe a recovery analysis method based on heart rate variability developed by Firstbeat Technologies Ltd. Parts of this paper may have been published elsewhere and are referred to in this document.

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SUMMARY

- Regular physical activity (PA) has significant benefits for health. It can reduce the risk of cardiovascular diseases, diabetes, colon and breast cancer, depression, a hip or vertebral fracture, and help in controlling weight.
- Physical inactivity is a world-epidemic, and a significant risk factor associated with lifestyle related non-communicable diseases.
- Physical fitness level is associated to lower all-cause mortality and reduced morbidity, especially related to chronic diseases.
- Physical fitness is related to quality of life. Certain level of fitness is required to be able to perform different activities, and the importance of fitness increases along with advancing age as fitness decreases inevitably as we age.
- International physical activity recommendations suggest 150min of moderate intensity or 75min of vigorous intensity PA per week, or a combination of these two. In addition, muscle strengthening activities should be performed two or more times per week.
- Firstbeat has developed measures to analyze how well a person fulfills the physical activity recommendations and what is the impact of daily PA on fitness development.
- Firstbeat helps to understand the effects of daily lifestyle choices on health, quality of life, and fitness, and to make informed decisions of daily activities.

KEY TERMS

- **Physical activity** = Any bodily movement produced by skeletal muscles that increases energy expenditure.
- **Physical inactivity** = Lack of adequate physical activity. Identified as the fourth leading risk factor for global mortality causing an estimated 3.2 million deaths globally each year.
- **Physical Activity Recommendations** = Internationally used, science-based recommendations determining the quantity and intensity of physical activity for different population groups (children, adults, elderly) for acquiring health benefits.
- **MET (Metabolic Equivalent)** = Measure of exercise intensity. The ratio of metabolic rate (energy consumption) during physical activity to a reference metabolic rate, set by convention to 3.5 ml O₂/kg/min. Physical activity at 3 MET level require three times the energy that an average person consumes at rest (e.g., sitting quietly).
- **VO₂max** = Maximal oxygen uptake - a measure of aerobic fitness level and aerobic capacity. Depicts the highest level of oxygen uptake a person can reach.
- **% of VO₂max** = Another measure of exercise intensity. Level of oxygen consumption / energy expenditure in the body as compared to person's maximal oxygen consumption.
- **Physical Activity Index** = A measure by Firstbeat depicting acquired health effects of daily physical activities (0-100).
- **Physical Activity Score** = A measure by Firstbeat depicting both health and fitness effects of daily physical activities (0 - ~2000).

HEALTH AND FITNESS BENEFITS OF PHYSICAL ACTIVITY

The importance of physical activity for fitness and health

Physical inactivity and sedentary lifestyles constitute a worldwide epidemic, which according to some experts is the most important public health problem of the 21st century [1]. Physical inactivity inevitably results in lower aerobic fitness levels. Inactivity and poor fitness are associated with numerous health issues, including cardiovascular diseases, metabolic disorders (e.g. overweight, obesity, type-2 diabetes), musculoskeletal disorders, pulmonary diseases, cancer, psychological issues, etc. [2-8]. Consequently, poor aerobic fitness has also been associated with a marked increase in risk of premature death [5-7]. Regular physical activity and corresponding higher aerobic fitness levels, however, are associated with lower risk of premature death and morbidity. The physiological mechanisms through which physical activity can improve health while reducing risk of disability and premature death are presented in Figure 1.

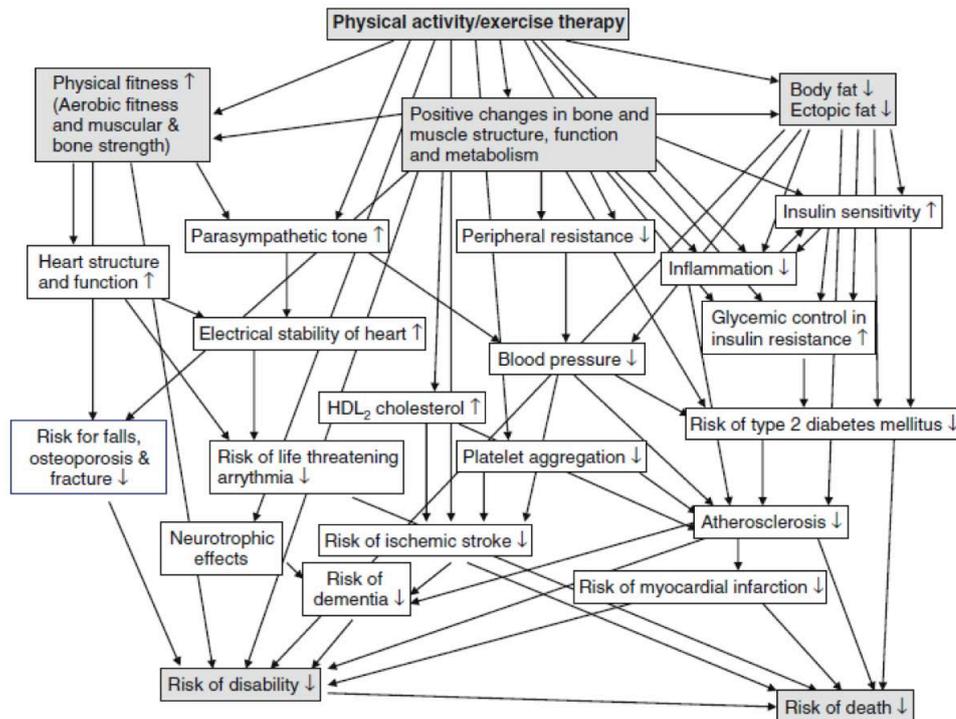


Figure 1. Mechanisms of how physical activity enhances health [4].

Improvements in aerobic fitness have been positively shown to reduce all-cause mortality [8]. Further, although aerobic fitness typically declines with age, achieving a higher fitness category can help maintain functional ability through retirement and old age. [9]. In practical terms, a 10% increase in aerobic fitness, measurable in terms of maximum oxygen consumption capacity (VO_{2max}), for a person with poor aerobic fitness can reduce mortality risk by 15% and extend good quality-of-life abilities by 10 years. Regular physical activity enhances recovery and restoration as manifested by improved balance in the autonomic nervous system discernible through analysis of heart rate variability (HRV) data. Higher physical activity levels are also associated with a reduced presence and magnitude of physiological stress reactions [10].

How much physical activity is enough to achieve health benefits?

Although the link between physical activity and health is clear, many people struggle to consistently reach recommended weekly targets. Specific exercise plans get interrupted by busy work schedules and the changing commitments of daily life. Diverse exercise prescriptions from health organizations and opinion leaders can also complicate the subject. It is, therefore, often difficult for individuals to know precisely what they should do and how best to exercise to achieve health and fitness benefits. A tool capable of automatically assessing the totality of physical activity performed in everyday life and clearly indicating whether sufficient physical activity levels been achieved would clearly be of great help to many people.

From a health perspective, it is important to develop endurance, muscular strength and flexibility. The effects of aerobically dependent endurance activities are focused on the heart, lungs and respiratory system, whereas strength and flexibility training affect the muscles and joints. Endurance activities include e.g. running, hiking, biking, cross-country skiing, swimming, ball games. Strength and flexibility exercises include e.g. gym training, group exercise (dance, aerobics), heavy physical work, yoga, Pilates, stretching, and coordination exercises.

The latest international prescriptions for physical activity recommend at least 150 minutes of moderate-intensity physical activity per week, or alternatively, 75 minutes of vigorous-intensity physical activity per week [11-14]. These can be combined and divided into shorter periods, but to maximize potential benefits, episodes of physical activity should be at least 10 minutes in duration. Performing 30 minutes of moderate-intensity activity five times a week, for example, would satisfy these recommendations. In addition to endurance type activities, muscular strength and mobility should be trained at least twice each week.

According to recommendations, health benefits associated with regular physical activity are likely to increase as activity levels increase. This relationship holds up to 300 minutes of moderate-intensity activity, or 150 minutes of vigorous-intensity activity per week (i.e., twice the minimum recommendations) [11-14].

Recent research suggests that satisfying weekly physical

activity targets with efforts performed one or two days each week can produce comparable health benefits. Efforts by these “weekend warriors,” and others who compile their weekly targets in 1-2 sessions, may be sufficient to reduce all-cause, cardiovascular disease, and cancer mortality risks, despite not strictly adhering to commonly recommended distributions of weekly activity [15].

Terms and methods for the assessment of physical activity intensity

Historically a variety of terms have been used to describe intensity as it relates to physical activity. This has led to some confusion, particularly as many of these terms have both clinical and everyday usages. These include terms like resting level, very light, very weak, easy, sedentary, weak, light, moderate, vigorous, high, strenuous, intense, hard, very hard, and very high. The currently used terms in international recommendations for physical activity are clearer and rely on well-defined categories of moderate- and vigorous-intensity activity [16].

In addition to terminological challenges, several different methods of measuring intensity are commonly used. These include assessing intensity as a percentage of a person’s 1) maximum heart rate (%HRmax); 2) heart rate reserve, the difference between a person’s maximum and minimum heart rates (%HRR); 3) maximum oxygen consumption rate (%VO₂max or %METmax); 4) oxygen consumption reserve (%VO₂R); and 5) intensity in terms absolute oxygen consumption rates or metabolic equivalent of task (MET). Of these approaches, oxygen consumption-based methods are generally considered the most accurate for assessing the intensity of aerobic activity and used e.g. by the American College of Sports Medicine (ACSM) as the reference method.

When using oxygen consumption -based approach both absolute and relative to individual fitness level parameters can be used. Absolute oxygen consumption rates are described in

frequently normalized for body weight and expressed in milliliters of oxygen per kilogram of body weight per minute (ml/kg/min). An alternative measure for this purpose is metabolic equivalent of task (MET).

MET is a physiological concept used to help assess the absolute energy demands of different activities. 1 MET represents the oxygen consumption rate of an average person sitting at rest, which is set by convention to be 3.5 ml/kg/min, regardless of a person’s age or body composition. While 1 MET represents an average person sitting at rest, 15 MET represents an oxygen consumption (or energy expenditure) rate of 15 times resting levels. An activity corresponding to an exertion of 15 MET would be running at around 15 km/h.

Assessing physical activity in terms absolute oxygen consumption offers the advantage of being able to evaluate the actual work that has been performed by the person. The downside is that these metrics fail to account, in any way, for differences in maximum consumption capacities between persons.

Expressing oxygen requirements and consumption rates as a percentage of an individual’s maximum oxygen consumption rate (VO₂max or METmax) offers a solution. The approach is more individual, but the downside is a dependency on knowledge of the person’s VO₂max / METmax.

As a practical example, exercising with an oxygen consumption rate of 60% of VO₂max is a very different activity for someone with VO₂max of 21 ml/kg/min (6 MET) compared to someone with a VO₂max of 70 ml/kg/min (20 MET). The former is walking slowly (60% of 6 MET = 3.6 MET), whereas the latter is running at a speed around 12 km/h (60% of 20 MET = 12 MET)! Still each may perceive they are performing comparably challenging activities relative to their own performance capacity. Figure 2 shows the huge differences that may be present when evaluating physical activity intensity as absolute or relative-to-fitness level units [16].

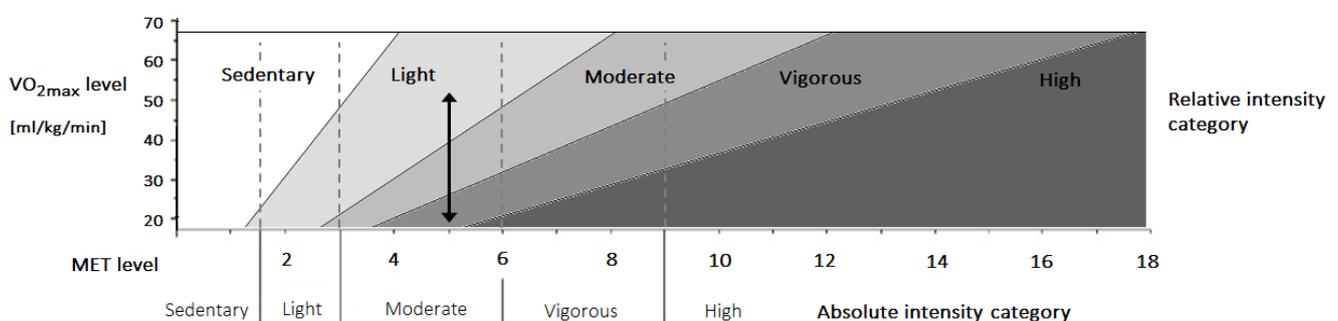


Figure 2. Exercise intensity categories represented in absolute and relative units. Activity which is moderate in absolute terms, e.g. 5 MET, can be vigorous or even high intensity activity for a person with low VO₂max but light activity for a person with high VO₂max (visualized by an arrow) [modified from 16].

SUFFICIENCY OF PHYSICAL ACTIVITY

Utilization of oxygen consumption rates

Firstbeat's analysis of physical activity benefits from an ability to accurately assess intensity in terms of oxygen consumption. This non-invasive method utilizes a combination of heartbeat measurement (PPG or ECG), respiration rate (derived from R-R intervals), and on/off-response information. The method can be enhanced with the introduction of external work data when available. This includes, for example, GPS- or accelerometer-based speed and acceleration data, step rates, cycling power, and elevation information. For more detailed information, see Firstbeat White Paper: VO₂ Estimation Method Based on Heart Rate Measurement. [17].

Assessing health effects of physical activity

The Firstbeat Lifestyle Assessment is a professional-grade health and wellness check. Insights included in the assessment are based on a scientific analysis and interpretation of heart rate variability (HRV) data, typically 72-hours, recorded by the participant in the real-world conditions of everyday life. The Firstbeat Lifestyle Assessment provides insight into topics of stress, recovery, sleep, and physical activity.

As part of the assessment, physical activity is routinely identified, analyzed, and evaluated on the basis of producing health benefits. To this end, a Physical Activity Index is produced using a 0 to 100 feedback scale (0-30 = poor, 30-59 = moderate, and 60-100 = good health effects). In principle, as reflected in Firstbeat analytics, all physical activity produces some benefit. The degree of benefit achieved varies according to the duration and intensity of the activity.

According to the Physical Activity Index, 60 points per day indicates physical activity sufficient to produce significant health benefits. This level of physical activity represents approximately 30 minutes of physical activity performed at moderate-intensity, or 20 minutes at vigorous-intensity levels. Light-intensity activities still accrue points, but at a substantially lower rate.

Assessing fitness effects of physical activity

Firstbeat determines the impact of physical activity on aerobic fitness, measurable as VO₂max, by assessing disturbance of the body's homeostasis. This is achieved using a combination of physiological and mathematical modeling techniques to predict excess post-exercise oxygen consumption (EPOC). When placed into the context of a person's current fitness level and activity history, EPOC values provide the foundation for Aerobic Training Effect (AeTE) scores.

Aerobic Training Effect is reported on a scale of 0.0 - 5.0, which

is used to describe the impact of an activity session on the development of aerobic performance capacity (VO₂max). A session can be determined to have no effect (AeTE 0.0 - 1.0), a minor effect (AeTE 1.0 - 1.9), a maintaining effect (AeTE = 2.0 - 2.9), an improving effect (AeTE = 3.0 - 3.9), or highly improving effect (AeTE = 4.0 - 4.9). An AeTE score of 5.0 indicates that the body was temporarily overloaded. For more information on Aerobic Training Effect, please see Firstbeat White Paper: EPOC Based Training Effect Assessment [18].

Intensity categories used by Firstbeat

Light physical activity

During light physical activity, oxygen consumption is elevated from resting level and exceeds 2 METs, but the rate of oxygen consumption is still less than 40% of VO₂max. This kind of activity does not cause a noticeable increase in respiration rate. It is good to perform some light physical activity each day, because it accelerates the body's metabolism and promotes recovery between harder workouts. On its own, however, light physical activity is insufficient to improve aerobic fitness levels and the health effects are limited. Examples of light physical activity include housework, brisk walking, heavier household work and gardening. Typical heart rates during light physical activity range from 80 - 120 bpm depending on the person's maximum heart rate and current fitness level.

Moderate physical activity

During moderate physical activity, oxygen consumption exceeds 3 METs, and the relative oxygen consumption rate is 40 - 60% of VO₂max. For highly-fit individuals, achieving an oxygen consumption rate of 40% of VO₂max may already require a substantial level of activity. For a person with a VO₂max of 70 ml/kg/min (20 METmax) achieving a relative oxygen consumption rate of 40% equals to an absolute rate of 8 MET. Accordingly, Firstbeat assesses all activity with an intensity over 6 MET to be moderate physical activity, as it already breaches the threshold for vigorous-intensity in absolute terms. Moderate physical activity provides health effects for the respiratory, cardiovascular, and musculoskeletal systems as well for lipid and glucose balance of the blood. Typical heart rates during moderate physical activity range from 110 - 150 bpm.

Vigorous physical activity

During vigorous physical activity, oxygen consumption exceeds 3 METs and 60% of VO₂max, or the MET level is over 9, as it already breaches the threshold for high-intensity in absolute terms (similar reasons as with moderate physical activity). Vigorous physical activity causes sweating and breathlessness, and it significantly impacts overall metabolism and health of the heart, vascular system, and lungs. This type of activity has a substantial impact on the development of aerobic fitness. Typical heart rates during vigorous physical activity range from 140 - 180 bpm.

Assessing the combined health and fitness effects of physical activity

While there are options for assessing the impact of physical activity recorded during ambulatory measurements on health or fitness independently, a single measure capable of reporting on health and fitness benefits together has been lacking.

Physical Activity Score (PAS) offers a viable solution to this problem. It is a simple, easily-understood metric that combines the health perspective provided by the Physical Activity Index and the fitness perspective provided by Aerobic Training Effect. As a result, Physical Activity Score can communicate the health and fitness benefits of physical activity simultaneously in the form of a single number.

Connecting the health, fitness, and physical activity in this way clarifies and simplifies the complex and dynamic relationship between these factors. Feedback ensures that anyone can validate beneficial activities and learn what kinds of physical activity are needed to achieve health goals and to improve or maintain aerobic fitness.

Physical Activity Score is produced in accordance with the latest physical activity recommendations for public health and fitness [e.g. 11]. Points accrue at different rates according to intensity, mirroring ACSM physical activity guidelines. The sum of points earned from all recorded activities during the day result in a daily score. Physical Activity Score feedback is scaled according to studies of exercise science. It is relatively easy to achieve scores associated with health benefits and aerobic fitness level maintenance. To improve aerobic fitness, however, much more demanding efforts are required. The scale is easy to interpret as the accumulated single score directly determines daily benefit on health and fitness. The scaling is presented in the Table 1.

Table 1. Daily Physical Activity Score interpretation.

Physical Activity Score	Interpretation
≥1500	Increased risk of overload
≥500	Improves fitness
≥100	Good for health
0-99	Health benefits not yet reached

Like in the Physical Activity Index used in the Firstbeat Lifestyle Assessment, the daily target associated with health benefits can be achieved with either 30 minutes of moderate-intensity physical activity, or 20 minutes of vigorous-intensity activity. Points accrue exponentially according to intensity level, so that higher intensities yield points more quickly. Extra points are

awarded during an activity each time a new level of aerobic fitness benefits is achieved (i.e., a higher Aerobic Training Effect score).

The points used to provide Physical Activity Score feedback are individually calibrated and automatically personalized using the person's current age, gender, aerobic fitness level (VO2max) and activity history. VO2max is determined and updated during running or walking sessions. The rate at which points accumulate during an activity session is also influenced by the user's VO2max and activity history.

A person's current aerobic fitness level has a significant impact on the combination of activity duration and intensity that will disturb body's homeostasis and stimulate training adaptations. It is clear, then, that to be meaningful the limits set for "improving fitness" or "training overload" cannot be the same for everyone. To account for this fact, Firstbeat designed Physical Activity Score so that the dosage of physical activity needed to produce health benefits is roughly the same for everyone, but the dosage required to improve aerobic fitness levels varies greatly – depending on current fitness level and activity history.

For example, a person with a low VO2max and/or minimal activity history performing an ACSM-recommended 20 minutes of vigorous-intensity physical activity may score 500 points, indicating the effort was sufficiently challenging to improve aerobic fitness. A similar session for someone with an excellent VO2max may only yield 100 points, meaning that the effort produced health benefits and supported but did not improve fitness.

Vigorous-intensity efforts, or close to them, are practically necessary to improve aerobic fitness levels. Therefore, activities performed only at light- and/or moderate-intensity levels will typically only produce Physical Activity Scores in the range of health benefits. To improve fitness, absent vigorous-intensity efforts, lengthy durations are required. Table 2 presents examples of the amount of time required at different intensities to reach health and fitness improving limits.

Table 2. Physical activity durations required to reach health and fitness improving scoring in PAS for a person with good fitness level.

Intensity	Time required for health improving level	Time required for fitness improving level
Light	165min	Cannot be reached
Moderate	30min	~ 90min
Vigorous	20min	E.g. 30min at 65% or 20min at 70% VO2max

ACSM physical activity guidelines can be satisfied by achieving five 100-point days in a week, representing the minimum threshold for unlocking the health benefits of an active lifestyle. Scoring at least 500 points 2-3 times a week will likely result in an increase in aerobic fitness level (VO2max).

FIRSTBEAT PHYSICAL ACTIVITY METRICS IN SCIENCE

An extensive scientific study was conducted using the Firstbeat database to investigate how physical activity recommendations were met in a large sample of Finnish employees (N=9554) [19]. Amounts of moderate-to-vigorous-intensity (MVPA) and vigorous-intensity physical activity (VPA) were assessed using absolute intensity values (≥ 3 and ≥ 6 METs, respectively), which were detected using Firstbeat's oxygen consumption-based model of intensity assessment. Participants identified as fulfilling the aerobic physical activity recommendation of ≥ 150 minutes per week were determined using episodes of physical activity lasting at least 10 minutes and by multiplying accumulated vigorous-intensity minutes by 2 as recommended.

The study found that the percentages of participants fulfilling the international aerobic physical activity recommendations were highest for normal weight men (65%; 95% CI 62% to 67%) and lowest for obese women (10%; 95% CI 8% to 12%). The authors identified that the quantity of objectively measured physical activity is higher among men and higher during days off. It also decreases according to increases in BMI and age. The amount of vigorous-intensity physical activity performed by obese, overweight, and older female participants was very low. Based on a previous study conducted using questionnaires, the authors cited that approximately one-quarter to one-half of working-age adults in Finland fulfil the

current physical activity recommendations for aerobic activity. Objective measurements of physical activity by Firstbeat (men 54%, women 33%) were in line with these earlier findings when 10-minute episodes of exercise were considered [19]. Figure 3 shows the distribution of participants fulfilling physical activity recommendations by gender and weight categories. Weekly amounts of physical activity are calculated using the Firstbeat oxygen consumption (VO₂) based model and only considered episodes of continuous physical activity of at least 10 minutes in duration.

Another recent study [20] utilized a sample from the Firstbeat database to investigate the objective difference between using absolute and relative measures of intensity. The study examined 143,334 days of activity data recorded from 35,467 individual participants. The study found that, using absolute measures of intensity, it is easier for high-fit individuals to reach the recommended amounts of moderate-to-vigorous-intensity activity compared with low-fit individuals, easier for men compared with women, younger people compared with older, and lean compared with obese individuals. The authors concluded that when relative intensity measures are used to assess progress towards physical activity recommendations the frequency of reaching the target is more similar for low- and high-fit individuals.

Therefore, it may be preferable to prescribe and assess physical activity using relative intensity over absolute intensity classifications to facilitate moderate-to-vigorous-intensity activity for inactive, low-fit, and/or obese individuals [20]. Figure 4 on the next page shows the theoretical overlap between absolute and relative intensity categories between low- and high-fit individuals.

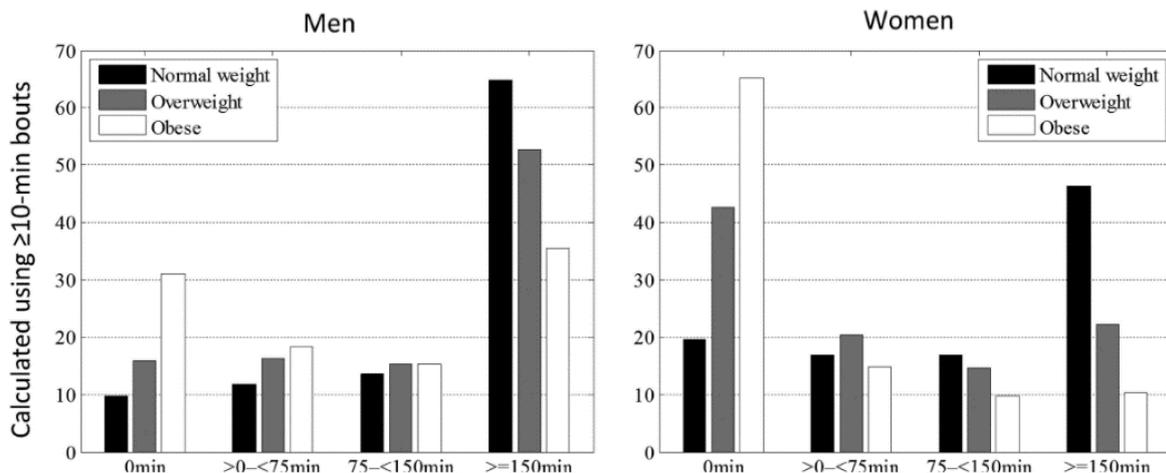


Figure 3. Proportion of participants fulfilling the PA recommendations measured by exercise bouts of at least 10min using Firstbeat heartbeat derived oxygen consumption. Both moderate and vigorous physical activity is considered and the amount of vigorous PA is multiplied by 2 to calculate the weekly amount of PA [19].

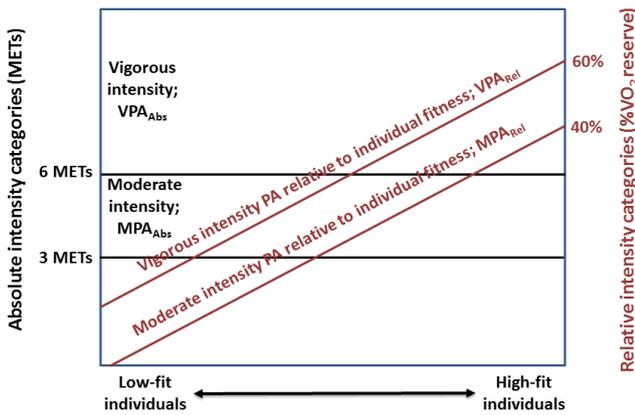


Figure 4. The overlap between absolute and relative PA intensities when fitness level is considered. For low-fit individuals it is difficult to reach recommended absolute exercise intensities due to poor fitness but for high-fit individuals the used absolute levels (3 and 6 MET) can be easy.

An internal Firstbeat examination of 155,000 days of activity data recorded in 2017, contained in the Firstbeat database, revealed an average Physical Activity Index of 48 (scale of 0-100). Individuals who self-reported being in good- or top-level fitness categories also most frequently described being satisfied with their own activity levels and fulfilled the physical activity recommendations. Individuals who self-reported being in poor- or moderate-level fitness categories were more likely to describe being unsatisfied with their physical activity levels and scored lower on the Physical Activity Index (Figure 5). Average recorded moderate- and vigorous-intensity minutes achieved by individuals in these different activity groups are presented in Table 3.

PA index and self-reported sufficiency of PA

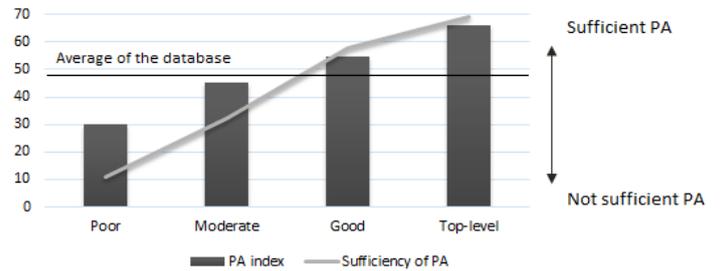


Figure 5. Physical activity index and self-reported sufficiency of physical activity in different activity classes from poor to top-level fitness in the Firstbeat database 2017 including 155,000 measured days.

Table 3. Physical activity minutes according to self-reported fitness level in the Firstbeat database 2017.

AC class / fitness level	Moderate PA min	Vigorous PA min	Physical activity index (0-100)
Poor	10min	2min	30
Moderate	13min	4min	45
Good	13min	9min	55
Top-level	16min	13min	66

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