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Estimation of Cardiopulmonary Fitness during Daily Activity

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서울대학교 대학원
협동과정 바이오엔지니어링

윤 치 열

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Interdisciplinary Program for Bioengineering,
Seoul National University
College of Engineering

Chiyul Yoon

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지도 교수 김 희 찬

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협동과정 바이오엔지니어링
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부위원장 ______ 김 희 찬 ______ (인)

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위 원 ______ 이 정 찬 ______ (인)

Abstract

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Chiyul Yoon

Interdisciplinary program for Bioengineering

The Graduate School

Seoul National University

Cardiopulmonary fitness (CPF), the ability to provide inhalational oxygen to the exercising muscle, is one component of health-related physical fitness — one of the main goals of exercise, and is related to all-cause and cardiovascular mortality. Increased fitness is associated with lower mortality. The maximum uptake of oxygen (VO_2max) is the representative index of CPF. Studies indicating a decrease in all-cause mortality with the improvement of CPF emphasize the importance of CPF in health care.

Nevertheless, CPF has not received due attention, at least in part because of the lack of practical and reliable methods to measure it.

Despite metabolic gas analysis during maximal exercise being the gold standard measurement of VO_2max, it is not safe for high-risk groups because of the requirement for high intensity exercise, and high levels of motivation are required to complete the test. The submaximal exercise test also requires specific equipment, and can be affected by familiarity with the test protocol. Numerous non-exercise estimation methods which use anthropometric parameters and individual self-reported physical activity, or pedometers. Non-exercise estimations do not measure biological responses to physical activity. Moreover, self-reported physical activity could be inaccurate.

Recently, CPF has been estimated by continuous HR and accelerometric physical activity monitoring with or without a specific exercise protocol. Fitter individuals with a higher level of VO_2max are assumed to be more active with a lower HR than unfit individuals with a lower level of VO_2max. Although these methods are simple and safe for high-risk groups, they also involve a specific exercise protocol that cannot be applied to daily life. VO_2max estimation without exercise however, requires prolonged measurement at least seven days with attached sensors, making these methods impractical.

The VO_2max of 23 healthy, sedentary men was measured by using the maximal exercise test. Corresponding heart rate and activity energy expenditure data were also recorded. The maximum activity energy expenditure was estimated by age, using the first 12 hours of activity energy

expenditure, and heart rate data recorded from 4 days of typical daily life. Participants were divided into training (n = 15) and test (n = 8) groups, according to activity energy expenditure, and a regression model for estimating VO_2max was developed.

The activity energy expenditure estimated from 12 hours of daily living correlated significantly with the measured VO_2max value, and recording beyond 12 hours did not improve the estimation. In addition, the estimated maximum oxygen uptake agreed with the measured maximum oxygen uptake value. The accuracy of the model compared well with previous maximum oxygen uptake estimation studies.

Key Words: Physical Fitness, Cardiopulmonary Fitness, VO_2max, Activity Energy Expenditure, and Regression.

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1. INTRODUCTION

1.1 HEALTH, PHYSICAL ACTIVITY AND FITNESS

The World Health Organization (WHO) has defined health as a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity (1). Health, health-related physical fitness and heredity all affect one another. Moreover, health-related physical fitness and physical activity affect one another (2).

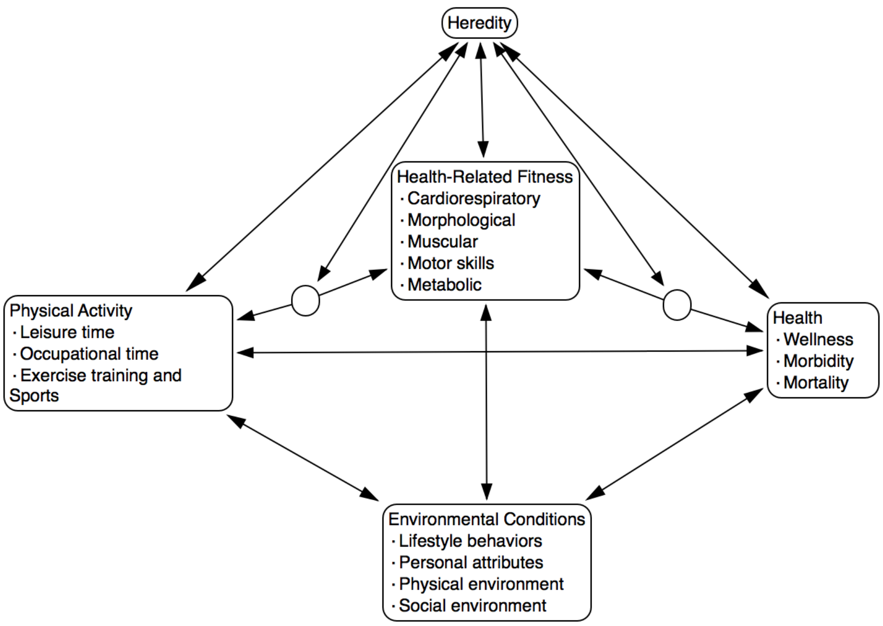

Figure 1 The relationships among heredity, physical activity, health-related physical fitness, health, and environmental conditions.

1.1.1 PHYSICAL ACTIVITY

Physical activity is any bodily movement produced by the skeletal muscles. Physical activity requires energy expenditure and provides health benefits. Exercise is a subset of physical activity; it represents planned, structured, and repetitive bodily movement aimed at improving or maintaining physical fitness (3, 4).

There are three methods for measuring physical activity. Criterion methods, such as doubly labeled water or indirect calorimetry, are accurate; however, they are not applicable to daily measurement because of their cost. Objective methods, such as accelerometers and pedometers, which are inexpensive, measure energy expenditure. Subjective methods are applicable in cohort studies; they quantify physical activity using self-reported questionnaires (2). Recently, many studies (5-14) that quantify physical activity using an accelerometer have been performed, and a number of commercial, off-the-shelf accelerometer-based physical activity devices are available.

1.1.2 PHYSICAL FITNESS

Physical fitness is a set of attributes that people have or achieve that is related to the ability to perform physical activity. Fitness is a synonym for capacity or ability. Physical fitness is defined as “the ability to carry out daily tasks with vigor and alertness, without undue fatigue and with ample energy to enjoy leisure-time pursuits and to meet unforeseen emergencies” (4).

It is well known that physical activity is positively correlated with physical fitness. Exercise is a subset of physical activity that is also strongly correlated with physical fitness (4, 15). Physical activity is an important risk predictor of coronary heart disease; physical fitness is more strongly correlated with coronary heart disease than physical activity is (16, 17). Individuals with a low level of physical fitness have a relative risk of cardiovascular disease (CVD) that is almost 8 times higher than that of individuals with a high level of physical fitness. The difference in mortality risk between fit and unfit groups is approximately double of the difference in mortality risk between inactive and active groups (18).

1.1.3 TYPES OF PHYSICAL FITNESS

Physical fitness is divided into two categories. One is health-related physical fitness, which is related to good health. Health-related physical fitness has five components: cardiopulmonary fitness (CPF), body composition, muscular strength, muscular endurance, and flexibility.

CPF is a major component of health-related fitness; it depends on the function of the circulatory and respiratory systems (19). CPF will be discussed in great detail later. Body composition refers to the relative amount of different types of body tissues (bone, fat, muscle) that are related to health. Muscular strength is the ability to execute high-intensity muscular activities. Muscular endurance, or muscular fitness, is the ability to produce and maintain muscular power by repeated contraction over a period of time. Flexibility is the ability to move a joint through its complete range of movement (20).

The other component of physical fitness is sport- or skill-related physical fitness. It has six components: agility, balance, coordination, power, speed, and reaction time. It is known that health-related fitness is more important to public health than skill-related fitness (4).

This thesis focuses on health-related physical fitness, especially CPF, because CPF is directly related to the heart's performance and to an individual's functional health status (20-23).

1.1.4 DEFINITION OF CPF

CPF is the same meaning as cardiorespiratory fitness, aerobic fitness, cardiovascular fitness, and functional capacity (20). CPF is defined as the circulatory and respiratory systems' ability to supply fuel during sustained physical activity and to eliminate fatigue products after supplying fuel (4, 24). CPF measurements can be useful to explain the functional status of the respiratory, cardiovascular, and skeletal muscle systems (24).

1.1.4.1 EXPRESSION OF CPF

Metabolic equivalents (METs) or maximal oxygen consumption (VO_2max, the volume of O_2 consumption in 1 kilogram of body weight during 1 minute, ml/kg/min) or the endurance time of an exercise test are commonly used to express CPF (24). VO_2max is the best indicator of cardiovascular functional capacity because it directly reflects maximal cardiac output (21, 25). VO_2max depends on the performance of the circulatory and respiratory systems, which deliver oxygen-rich blood to the cells and tissues, which consume oxygen during energy generation (26, 27). VO_2max is defined as the difference between the cardiac output function and maximum systemic arteriovenous oxygen difference (28) , when these values are obtained during an exertion at a maximal effort.

Equation 1 Definition of maximal oxygen consumption

$$\dot{V}O_2\ \mathrm{max}({}^{ml}/_{min \times kg}) = [Q\ \times (\ C_aO_2 - C_vO_2\ )]_{max}$$

, where Q is cardiac output (stroke volume × heart rate), C_aO_2 is the arterial oxygen content, and C_vO_2 is the venous oxygen content. The arteriovenous oxygen difference is ($C_aO_2 – C_vO_2$) (29).

VO_2max is stable, and it varies by 4-6% on repeated maximal exercise tests because VO_2max is minimally affected (2-3%) by ambient temperature and dehydration (21, 28, 30). Chronic obstructive pulmonary disease (COPD) patients show greater variation in VO_2max (6-10%) (26, 31).

1.1.4.2 CHARACTERISTICS OF CPF

CPF is determined by modifiable (physical activity, smoking, obesity, and medical condition) and non-modifiable (age, gender, and genotype) factors. Among these factors, physical activity is the most important for determining CPF (24).

The CPF of males is 10-20% higher than that of females because males have a higher hemoglobin concentration, a larger proportion of muscle in their body composition fitness, and a greater stroke volume of the heart (22). CPF decreases by approximately 10% per decade in nonathletic subjects because of reductions in stroke volume, maximal heart rate, blood flow to muscles, and skeletal muscle function. CPF increases by 3-6% when individuals are in their 20s and 30s and decreases by more than 20% after the age of 70s (22, 32, 33).

1.2 CPF AND MORTALITY

Evidence obtained from cohort or specific population studies has revealed a relationship between CPF and mortality. Steven N. Blair at the University of South Carolina has performed almost all of the CPF-related mortality research. His studies have measured CPF at an aerobic center since 1974 and have followed up the participants' health status, including mortality, cancer, obesity, physical activity, dietary patterns, hypertensive status, coronary heart disease (CHD), cardiovascular disease (CVD), and diabetes. His studies have found correlations between CPF and other factors in healthy subjects and older individuals.

In 2011, the American College of Sport Medicine published guidelines for prescribing exercise that maintains fitness in healthy individuals (34). The guidelines also emphasize that healthy people and those with a greater CPF show a decreased risk of clinical events (35-40).

1.2.1 HIGH CPF & LOW MORTALITY

Blaire et al. first found the influence of CPF and other precursors on cardiovascular disease and all-cause mortality. The participants in the study were aged 20-88 years, and 25341 men and 7080 women (unhealthy participants were 4802 men, 958 women) participated in the study. The researchers examined smoking habits, cholesterol levels, blood pressure, and health status and measured CPF based on the endurance time on the Bruce protocol test. CPF was used to divide the participants into three subgroups:

low 20% of participants were classified as low fitness, next 40% of participants were classified as moderate, and upper 40% of participants were classified as high fitness group. After the initial medical examination, the subjects were followed for 17 years of mortality surveillance.

The men showed a significant correlation between mortality and precursors of low fitness, smoking, abnormal ECG, chronic illness, and increased cholesterol level. Among the men, there was a clear decrease in mortality in association with increased fitness status. The women showed a correlation between mortality and precursors of low fitness and smoking status. The low fitness group showed the highest mortality regardless of health status, blood pressure, smoking status, and cholesterol. The women showed higher mortality in the low fitness group than in the other groups; however, mortality showed a vague trend in the moderate and high groups. The authors concluded that low fitness is an important precursor of mortality and that physicians should recommend that sedentary patients become active to reduce their risk of premature mortality (41).

More recent results from Blair's group cohort study are also available (24). The high CPF groups of males and females had an all-cause mortality rate that was lower (28-43% and 40-53%, respectively) than that of the low CPF group. The high CPF group also showed lower CVD mortality (25-47% and 37-70% for men and women, respectively) than the low CPF group.

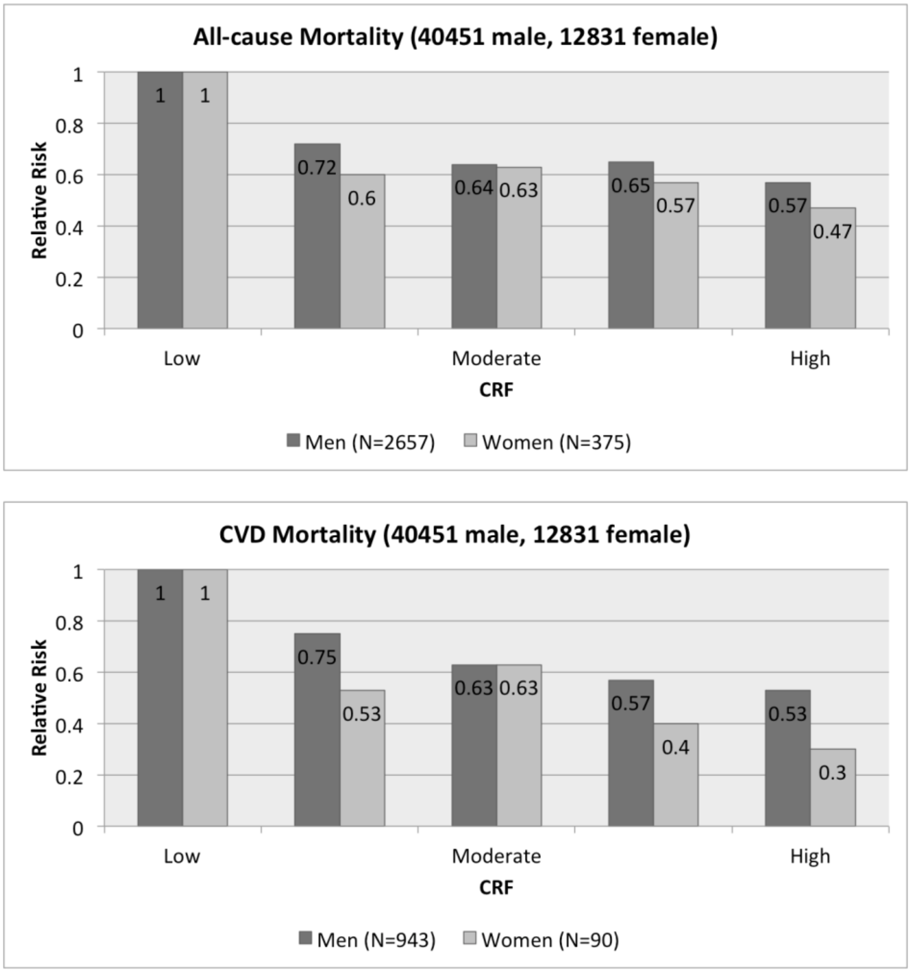

Figure 2 Relative risk of all-cause and CVD mortality according to CPF levels. The first quintile (high fitness) group shows the lowest risk relative to the 5th quintile (low fitness) group.

Sui et al. found that the prevalence of obesity increases with age, whereas physical activity level and CPF decrease. The authors examined the relationships among CPF, adiposity, and mortality in older people. The study participants included 2087 men and 517 women aged 60 years or older. Adiposity was determined by body mass index (BMI), waist circumference, and percentage body fat. CPF was also measured by the total endurance time on a maximal treadmill exercise test with a modified Balke protocol. The low fitness (unfit) group consisted of participants who were in the lowest 20% for each gender; all others were assigned to the fit group.

An average of 12 years of mortality surveillance was analyzed. The results indicated that the all-cause mortality risk was 47-70% lower in the fit group than the unfit group. The risk of all-cause mortality according to adiposity is clear; the mortality risk of the unfit group was 68-363% higher than that of the unfit group according to adiposity status. The death rate of the fit group was not significantly different among the BMI categories, whereas in the unfit group, the death rate was low among those with a moderate BMI (25.0 - 34.9) and high among those with a low or high BMI (under 24.9 or over 35.0). The study concluded that the low fitness group had a higher risk of all-cause death after adjustment for adiposity factors than did fit older adults (42).

Kodama et al. performed a meta-analysis for observational cohort studies that reported associations of CPF with CHD, CVD events, or all-cause mortality in healthy participants. Data were collected and analyzed in 33 studies of 102980 participants and 6910 cases of all-cause mortality and

84323 participants and 4485 cases of CHD and CVD. CPF was expressed in units of METs, which are defined as the ratio of the intensity of a physical activity to that of sitting at rest. Low, intermediate, and high CPF individuals were categorized according to the criteria of 7.9 and 10.9 METs.

The study found that the risk of all-cause mortality and a CHD/CVD event decreased by 13% and 15%, respectively, with a 1-MET increase. The risk of all-cause mortality was 70% higher in the low CPF group than the high CPF group, and the risk of CHD/CVD was 40% higher in the low CPF group than the high CPF group. The risks of all-cause mortality and CHD/CVD events were 56% and 47% higher, respectively, in the low CPF group than the intermediate CPF group. However, there were no significant differences in risk estimates for the low vs high CPF groups compared with the low vs intermediate CPF groups. The risk of all-cause mortality and CHD/CVD were also 13% and 7% higher, respectively, in the intermediate CPF group than the high CPF group. The authors concluded that high CPF was associated with a low risk of all-cause mortality and CHD/CVD events and that 7.9 METs would be used as the criterion for determining the risk of all-cause mortality and CHD/CVD (17).

1.2.2 WAYS TO IMPROVE CPF

Much evidence indicates that an active and fit individual can preserve functional ability and maintain health. Despite the evidence, the number of people performing regular, sustained and vigorous exercise did not increase from the mid-1980s to the 1990s in the United States (43). However, people who were sedentary or had a low fitness level may have wished to improve their CPF. Several appropriate exercise protocols can improve CPF.

1.2.2.1 LIFESTYLE CHANGE CAN IMPROVE CPF

Dunn et al. compared the 24-month effect of a lifestyle physical activity program with that of a traditional structured exercise program to increase CPF. The participants were 116 healthy men and 119 healthy women aged 35-60 years. Physical activity was measured by an interviewer-administered seven-day physical activity recall questionnaire (PAR) and validated by Tritrac R-3D in 33 participants. CPF was measured with a maximal graded treadmill test with ventilation gas analysis. The structured exercise group (n = 114) participated in a traditional exercise program, and the lifestyle group (n = 121) was encouraged to add at least 30 minutes of moderate-intensity physical activity.

Both groups showed significantly increased physical activity and CPF. The lifestyle groups showed a CPF increase of 1.58 ml/kg/min (21%) compared to baseline, and the structured group showed a CPF increase of 3.64 ml/kg/min (30%). The increased CPF that was found during the 6 months of participation decreased in the 18 months that followed. The lifestyle group showed a decrease of 0.7 ml/kg/min, and the structured group showed a decrease of 2.4 ml/kg/min.

The authors concluded that lifestyle changes related to physical activity were as effective at increasing CPF as the traditional structured exercise prescription. Sedentary individuals who lack in absolute amount of physical activity could be helped by this approach (44).

1.2.2.2 EXERCISE AMOUNT AND INTENSITY

Duscha et al. applied more intensive research to find a relationship between CPF and exercise intensity/amount. The authors divided their study participants into 4 groups: low amount and moderate intensity (LAMI, n = 25), low amount and high intensity (LAHI, n = 36), high amount and high intensity (HAHI, n = 35), and a control group (n = 37). The participants were 133 men and female aged 40-65 years, sedentary, nonsmoking, and overweight or with class-1 obesity (25 < BMI < 35). VO_2max was determined by a maximal exercise test on a treadmill with a ventilation gas analyzer. After 7-9 months of training in each group, VO_2max was remeasured and compared with the values from before training. VO_2max had increased by 6.5%, 11.0%, and 19.5% after the training in the LAMI, LAHI, and HAHI groups, respectively. The authors concluded that LAMI exercise (19 km/week at 40-55% of VO_2max) was sufficient to improve CPF and reduce cardiovascular risk (45).

1.2.2.3 EXERCISE TYPES

Helgerud et al. compared CPF improvement training at different intensities and with different methods matched for total work amount and frequency. The participants were 40 healthy, nonsmoking male participants with an average age of 24.6 years. VO_2max was measured by incremental treadmill exercise test with gas analyzer. Participants were randomly divided into four exercise tests groups: Long, slow distance running (LSD), lactate threshold running (LT), 15/15 interval running (15/15), and 4*4 min interval running (4*4 min). The training programs were performed three days per week for 8 weeks. VO_2max was remeasured and compared with the value before the training.

High aerobic intensity training in the 15/15 and 4*4 min groups resulted in absolute VO_2max (L/min) increases of 5.5% and 7.2%, respectively. The relative VO_2max (ml/min/kg) increased by 1.8%, 2.0%, 6.4%, and 8.8% in the LST, LT, 15/15, and 4*4 min training groups, respectively. The VO_2max of the 15/15 and 4*4 min groups differed significantly between pre- and post-training, and it also significantly differed between those two high aerobic intensity groups and the LSD/LT groups. The authors concluded that high aerobic intensity endurance interval training (15/15 or 4*4 min training) was significantly more effective than same amount of mild training for increasing VO_2max (46).

1.2.2.4 EXERCISE AMOUNT FOR PATIENTS

Rognmo et al. studied the relationship between exercise amount and CPF increase. Seventeen coronary artery disease (CAD) patients were divided into a high-intensity group (eight patients; mean age of 62.9 years) and a moderate intensity group (nine patients; mean age of 61.2 years). VO_2max was measured using a gas analyzer with a ramp protocol. The high-intensity exercise group performed at 85-95% of the maximum heart rate (HR), and the moderate intensity group performed at 65-75% of the maximum HR three times per week for 10 weeks. After the training period, VO_2max was measured again to reveal changes in CPF as a result of the exercise.

VO_2max increased by 17.9% in the high-intensity group and by 7.9% in the moderate intensity group. The CPF after the training period also differed between the groups ($p = 0.0011$), as did the CPF increase ($p = 0.006$). The authors concluded that high-intensity exercise can be more useful for improving CPF than moderate exercise in CAD patients. Because CPF is related to the risk of all-cause and CAD mortality, the present study can be helpful for determining the appropriate exercise prescription for an individual patient (47).

1.2.3 IMPROVED CPF LOWERS MORTALITY

A 1-MET increase in CPF is associated with a 13% lower all-cause mortality and a 15% decrease in CHD or CVD mortality (17, 18, 34, 36, 42, 48). A higher CPF improves insulin sensitivity, blood lipid and lipoprotein profiles, body composition, inflammation, and blood pressure and autonomic nervous system effects (24, 41); thus a higher CPF should be considered therapeutic in people with other risk factors such as blood pressure or glucose level.

Studies of the relationship between CPF and mortality have analyzed one-time measurements of CPF with follow-up mortality surveillance. A single analysis of CPF did not discriminate the influence of CPF with genetic or other confounding factors that affect mortality. Moreover, changes in CPF after a single measurement may affect the subsequent mortality risk (18). Two previous studies found a direct relationship between improved CPF and the risk of all-cause and CHD/CVD mortality in each individual.

Blair et al. performed a cohort study that showed a relationship between CPF improvement and the risk of all-cause and CVD mortality. The participants were 9777 men (6819 healthy, 2958 unhealthy) aged 20-82 years. CPF was measured twice at an average interval 4.9 years using the Bruce protocol treadmill endurance time. The unfit group was defined as the least fit quintile; the fit group included all other participants. To reveal the hypothesis that CPF improvements were caused by changes in physical activity patterns, a subgroup of 1512 men participated in an additional analysis of self-reported physical activity. Differences in the physical activity score between two examinations of groups 0, 1, and 2 (became most active) showed treadmill duration increases of 8, 41, and 93 seconds, respectively.

The age-adjusted all-cause death rate was highest in the stayed-unfit group (122/10000 man-years) and lowest in the stayed-fit group (39.6/10000 man-years). CPF improvement from unfit to fit showed a death rate of 67.7 per 10000 man-years, and all-cause mortality risk was 44% decreased relative to the stayed-unfit group. The age-adjusted relative risk of all-cause and CVD mortality relative for the stayed-unfit group is shown in the figures below (18).

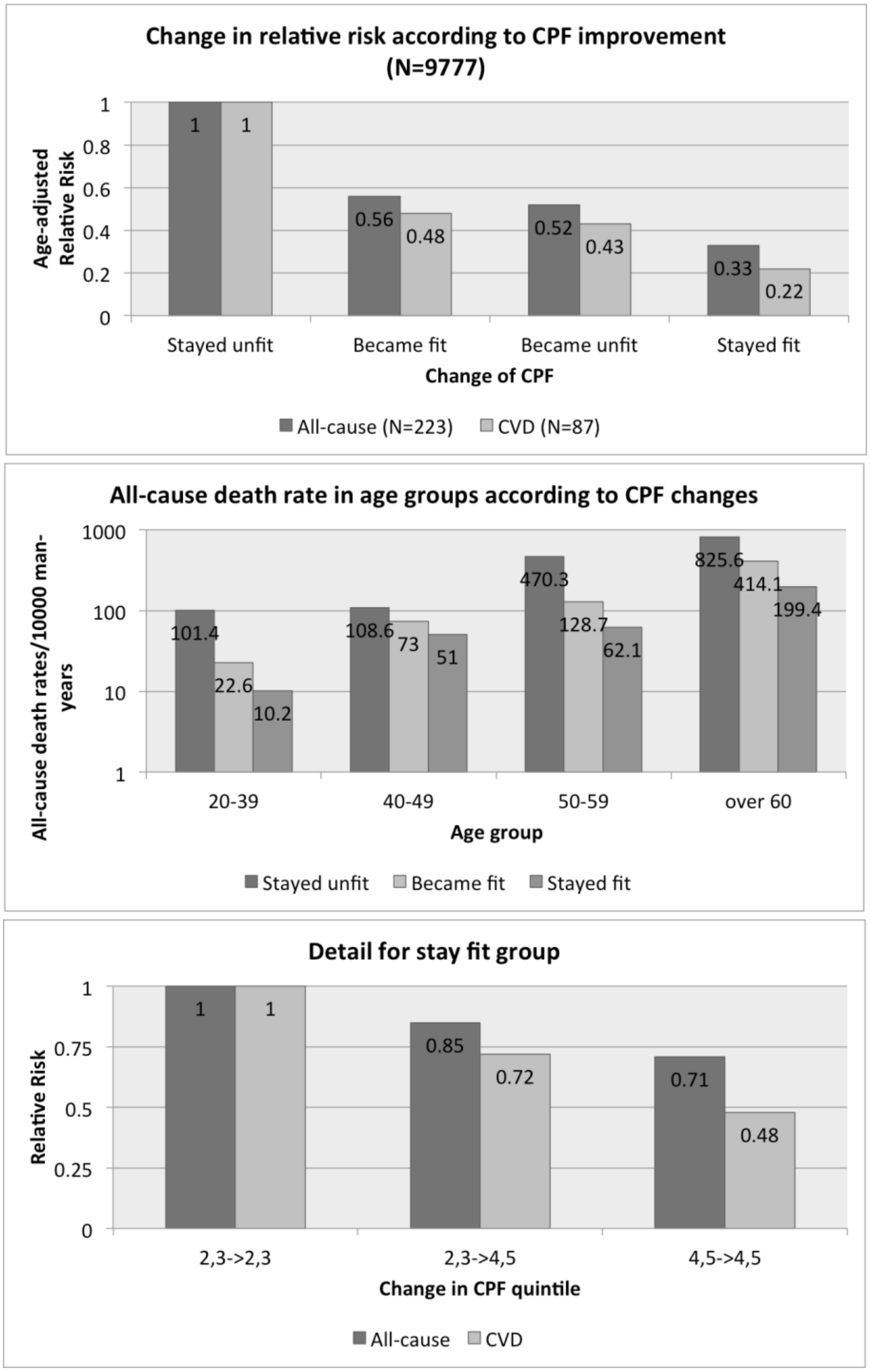

Figure 3 Change in relative risk according to CPF improvement

Erikssen et al. also studied the effect of sequential changes in physical fitness and mortality. The participants were 2014 men aged 40-60 years. The first CPF measurement was performed by incremental exercise with a cycle ergometer in 1972-1975. Physical fitness was defined as total work capacity divided by body weight (kJ/kg). The second CPF measurement was performed using the same method to measure CPF with the 1756 original participants who were still alive in 1980-1982. Among the 1756 participants, 328 participants were excluded because of diseases. Finally, 1456 participants were included in the analysis and followed up until December 1994.

The CPF level of the second test and the risk of all-cause and CVD mortality had a gradual inverse relationship. CPF improvement was associated with a significantly lower risk of all-cause and CVD mortality. The relative risk of all-cause mortality decreased by 20%, even among unfit individuals who showed little improvement in CPF. These results are similar to those of a previous study (18) showing mortality trends according to CPF changes (49).

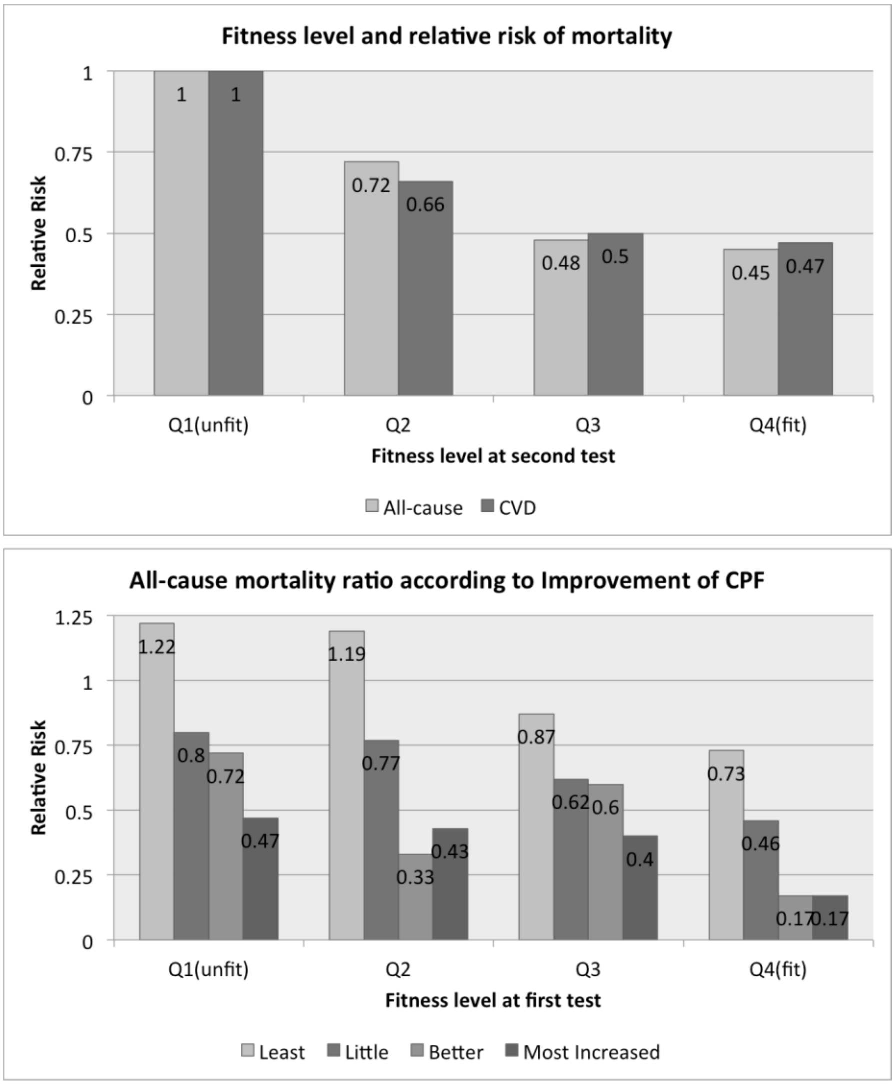

Figure 4 Changes in relative risk according to CPF improvement

1.3 CPF MEASUREMENTS

Many CPF measurement methods have been developed in recent decades. These can be categorized as protocol-based or non-protocol-based tests. Regardless of the protocol, all tests originated from the relationship between physical activity and physical fitness.

1.3.1 PROTOCOL-BASED TEST

The protocol-based CPF measurement test is divided into maximal or submaximal exercise tests. CPF can be measured directly from expired gas analysis with a maximal exercise test or estimated through various submaximal exercise tests.

1.3.1.1 MAXIMAL EXERCISE TEST

Maximal exercise tests are the gold standard and are preferred when accuracy is important, as in elite athletes or patients who require an exercise prescription according to their CPF results. In sports settings, accuracy and precision are important for detecting variations of VO_2max over time (21). The maximal exercise test is appropriate for healthy participants because of the physical burden encountered during the tests. Nevertheless, the maximal exercise tests are recommended for most research because the maximal exercise test is more precise than other methods (24).

In clinical settings, electrocardiography, blood pressure, oxygen saturation, and O_2 and CO_2 concentrations in ventilation gas are also analyzed during the maximal exercise test (20). Theoretically, CPF is defined as the plateau of VO_2 with further workload increases during the maximal exercise test. When no plateau is detected, VO_2max is expressed as VO_2peak. VO_2max and VO_2peak are the same in some individuals; however, this association is often incorrect (22, 26, 50). There are three well-known maximal exercise protocols conducted on treadmills or cycle ergometers. These are the Bruce protocol, the Balke-Ware protocol, and the Ball State University protocol (20). The Bruce protocol is the most widely used maximal exercise protocols (51).

1.3.1.2 SUBMAXIMAL EXERCISE TEST

The maximal exercise test could be replaced by the submaximal exercise test, which measures HR or exercise time to exhaustion, when experts or equipment are unavailable (24, 26). The submaximal exercise test originated from the linear relationships between oxygen uptake and mechanical power output and/or HR (21, 26, 52).

The submaximal exercise test can also be performed using a treadmill or cycle ergometer and during field activity (walking, running, and step counting). A treadmill is adequate for clinical or gym testing because the speed and incline are precisely controlled by the physician. A cycle ergometer can also accurately determine an appropriate workload for patients who are obese, pregnant, or at risk of falling. However, a treadmill requires some skill to use without problems, so a learning effect and inconvenience exist for first-time users. An ECG may be noisier than a cycle ergometer submaximal test (21).

Walking is appropriate for normal people without lower limb impairment and obese or elderly people who must avoid running. Running is appropriate for young, healthy people. A step test can be used in large populations; thus, it is ideal for occupational testing (21, 53).

VO_2max estimation from the submaximal exercise test shows little variation compared with the maximal exercise test because the same amount of motivation was required to achieve the same VO_2max using a maximal exercise test (21). Thus, the day-to-day variation in VO_2max at maximal levels of exercise may be 12% more varied than the VO_2max at submaximal levels of exercise in young, healthy men and women (54).

1.3.1.2.1 CHARACTERISTICS OF THE SUBMAXIMAL TEST

The Astrand-Ryhming test is a type of step test that is appropriate for fit individuals (R = 0.69 - 0.92) (55). The Mcardle step test shows a high test and retest correlation. It is commonly used when a large number of participants was test simultaneously (56). The one-mile walk test (Rockport test) is appropriate for those who are sedentary, irregularly active, and rarely able to run because of injury (R = 0.92 - 0.93, SEE = 0.325 L/min). The Rockport test estimates VO_2max using a participant's body weight, timed duration of walking, and HR at the end of the test (20, 26, 57). The Harvard 2 step test is used in medicine to aid in the diagnosis of heart disease (58). In the 12-min walk/run test, participants try to achieve the maximum distance in 12 min by walking, running, or a combination of both (R = 0.9 by (59), other researchers found that R = 0.13) (20, 26).

The shuttle walk test is suitable for pulmonary patients (R = 0.68 - 0.88) (60). The sinocolfi step test is appropriate for lupus patients, hypertensive patients, and elderly patients after hip replacement (61, 62). The Canadian aerobic fitness test (Canadian home fitness test) was designed to promote fitness testing at home (R = 0.79 - 0.905, SEE = 4.08 ml/kg/min) (26), and the modified Canadian step test is appropriate for elderly people (63). Arm-cranking test and the wheelchair test are suitable for those with lower limb impairment (64, 65). The single-stage submaximal treadmill walking test (R = 0.96, SEE = 4.85 ml/kg/min) showed a high correlation with the maximal exercise test. The 20-meter shuttle test was devised for children, adults attending fitness classes, and athletes (R = 0.71 - 0.95, SEE = 5.9 ml/kg/min) (26).

1.3.2 NON-PROTOCOL BASED TEST

Some studies have examined CPF estimation without using exercise; instead, they used personal data gathered by self-reported questionnaires about subjective physical activity. These estimations have been shown to be less accurate than maximal exercise test results; however, their accuracy has been shown to be comparable to that of submaximal exercise tests (57, 66-71)

1.3.2.1 MEASURING ACTIVITY USING SUBJECTIVE METHODS

Jackson et al. used gender, age, body composition (% of body fat by skin fold), BMI, and self-reported physical activity to estimate and cross-validate VO_2max with 2009 participants (9.7% female). The correlation coefficient between the estimated and measured CPF was 0.78 - 0.81, and SEE was 5.3 - 5.6 ml/kg/min (70). Whaley et al. developed and cross-validated an estimation model based on age, gender, resting HR, weight, % body fat, smoking, and physical activity with 2350 men and women. The R^2 was 0.733, and the SEE was 5.38 ml/kg/min (68).

Jurca et al. compared three large cohort studies that estimated CPF using a non-exercise model. The National Aeronautics and Space Administration/Johnson Space Center (NASA, 1458 men, 405 women, ages 20-70 years, using the Bruce protocol), the Aerobics Center Longitudinal Study (ACLS, 35826 men, 10364 women, ages 20-70 years, using the modified Balke protocol), and the Allied Dunbar National Fitness Survey (ADNFS, 853 men, 853 women, 20-70 years, submaximal treadmill test with ventilation gas analysis) studies used gender, age, measured height and weight for BMI, resting HR, and self-reported physical activity levels (SR-PA) to develop estimation models. Each study had a different self-reported physical activity score; Jurca et al. reanalyzed each score system and developed a universal score (SR-PA). R was 0.76 - 0.81, R^2 was 0.58 - 0.65, and SEE was 1.45 - 1.97 METs (equal to 5.075 - 6.895 ml/kg/min). One estimation model was applied to the other two datasets for cross-validation (R = 0.72 - 0.8) (72).

Wier et al. developed three estimation models using age, gender, self-reported physical activity status scale (PASS), waist girths (WG), %fat by skin fold test, and BMI with 2417 men and 384 women. Three models were developed, all of which used age, gender, and PASS. The common variables with the WG model showed R = 0.81 and SEE = 4.8 ml/kg/min; with the %Fat model, R = 0.82 and SEE = 4.72 ml/kg/min; and with the BMI model, R = 0.8 and SEE = 4.90 ml/kg/min. All of the estimation models showed similar performances; however, they were inaccurate for under 30 and over 50 ml/kg/min of VO_2max (73).

Nes et al. used similar variables as in (73) to estimate VO_2peak except for the exclusion of resting HR. The participants included 4260 subjects, 17.7% of whom did not achieve VO_2max criteria (the plateau of oxygen consumption during increased workload or respiratory exchange ratio over 1.05); the term "VO_2peak" was used instead. The independent variables were age, physical activity index by questionnaire (exercise frequency and intensity), waist circumference, and resting heart rate. The R value was 0.57 - 0.78, R^2 was 0.32 - 0.61, and SEE was 5.7 - 7.53 ml/kg/min (12.8% - 17%) for men; R was 0.56 - 0.75, R^2 was 0.32 - 0.56, and SEE was 5.14 - 6.35 ml/kg/min (14.3% - 17.7%) for women. The agreement of the four categories' classification between the measured and estimated VO_2peak was 39.9 - 65.2% for women and 39.9 - 68.4% for men (74).

1.3.2.2 MEASURING ACTIVITY USING OBJECTIVE METHODS

Moreover, recent studies have examined the estimation of CPF with objective physical activity monitors, such as accelerometers or pedometers, and have reported the relationship between pedometer-determined physical activity and VO_2max (75-78).

1.3.2.2.1 MEASUREMENT OF ONLY PHYSICAL ACTIVITY

Cao et al. developed and cross-validated measurements using a physical activity index that was measured using a pedometer. The participants were 189 Japanese women aged 20-69 years. The prediction group had 87 subjects, and the validation group had 102 subjects. VO_2max was measured using a graded exercise test with a cycle ergometer and a ventilation gas analyzer. The participants wore a pedometer on the right midline of the thigh for 7 days of waking time to measure their step count (SC). The correlation between SC and VO_2max was 0.26. An estimation model was developed using age, BMI, and SC as independent variables. R was 0.71 and SEE was 5.33 ml/kg/min for the prediction group, and R was 0.81 and SEE was 3.25 ml/kg/min (10.9%) for the validation group. The limitation of this study was the use of SC, which could not reflect the intensity and amount of physical activity (75).

Cao et al. performed another study to improve on the previous study. They used an accelerometer instead of a pedometer to detect activity intensity in this study. The participants were 148 Japanese women aged 20-69 years. Several estimation models were developed using different independent variables, including age, BMI, waist circumference, SC, moderate to vigorous physical activity, and vigorous physical activity. R was 0.805 - 0.863, SEE was 2.981 - 3.517 ml/kg/min, R_{press} was 0.788 - 0.852, SEE_{press} was 3.054 - 3.628, and R^2 was 0.648 - 0.716. A significant underestimation of VO_2max among individuals with high fitness individuals (over 37 ml/kg/min) has been consistently observed in the previous studies (73). The limitation was the participants' generalizability and the accelerometer's technical problems, namely, that is does not capture all types of physical activity, such as swimming or cycling (79).

Novoa et al. used pedometers with 38 patients who had undergone lung resection surgery. A pedometer is light and portable enough to use even with unhealthy participants. The pedometer was used for an average of 26.2 days to measure the mean daily values of total steps, aerosteps, and duration of aerobic activity distance. The daily moving distance measured by the pedometer and VO_2max (measured using gas analysis with the Wassermann protocol) showed the highest correlation (R = 0.44) among all pedometer-related variables. The model using mean daily distance showed R^2 = 0.812, and the model using mean daily distance and a lung-related parameter (diffusing capacity of the lung for carbon monoxide, DLCO%) showed R^2 = 0.935 (80).

1.3.2.2.2 MEASUREMENTS OF PHYSICAL ACTIVITY AND HR

In addition to CPF estimation using only objective physical activity, four previous noteworthy studies used the relationship between objective physical activity and physical response (HR) to estimate CPF.

Weyand et al. were the first to use physical activity and associated physical response. The participants in their study were 18 men and 18 women aged 18 - 37 years. The authors divided the subjects into an experiment group (n = 18) and a validation group (n = 18). VO_2max was measured using a progressive-speed, discontinuous, horizontal treadmill test to volitional fatigue and a gas analysis of the ventilation gas gathered in a Douglas bag. The authors invented an accelerometer-based foot pod device that measured the foot-ground contact time (tc) during the treadmill test. The correlation coefficient between VO_2max and the devised aerobic fitness index (AFI, HR/tc) was 0.9. The equation for VO_2max estimation was $11.1 + 34.4 \times$ AFI in men and $10.3 + 30.9 \times$ AFI in women in the experiment group. The correlation coefficient was 0.84 between measured VO_2max and estimated VO_2max by using the equation of prediction group to the validation subjects' values (81).

Plasqui et al. performed important studies that used accelerometers and HR sensors during daily activity with no exercise protocols. They focused on the fact that the submaximal exercise test originated from the relationship between VO_2max and HR at specific exercise intensities and used the same relationship to estimate VO_2max by measuring the intensity of physical activity and the corresponding HR. The basic principle of estimation was that individuals with a high level of fitness can perform high intensity physical activity while sustaining a low HR, unlike individuals with a low level of fitness.

The participants were 10 men and 15 women aged 18-50 years. VO_2max was measured by incremental testing with a cycle ergometer. The independent variables were body mass (BM), height, fat-free mass (FFM), and the ratio of HR to accelerometer counts per minute (HR/ACM). A polar HR monitor and a Tracmor tri-axis accelerometer measured HR and ACM, respectively, for seven consecutive days without any exercise protocol. A long measurement duration was needed to obtain a variety of HRs and physical activity levels. One average value of HR/ACM for the entire seven days was calculated for estimation.

The correlation coefficient between HR/ACM and VO_2max was -0.48. The estimation model with FFM, age, and HR/ACM showed R = 0.87, R^2 = 0.75, and SEE = 363 ml/min (12.2%, divided by mean BM, 5.31 ml/kg/min). The estimation model using age, BM, and HR/ACM showed R = 0.84, R^2 = 0.71, and SEE = 409 ml/min (13.7%, divided by mean BM, 5.99 ml/kg/min) (82).

The authors validated the estimation model (using age, gender, BM, and HR/ACM) with another cross-validation group (14 men and 12 women). The participants' average HR and ACM were determined by measurements taken over 740 minutes per day. The estimated VO_2max value for the cross-validated group differed significantly from the measured VO_2max. The authors regrouped all of the participants into experiment and cross-validation groups according to their individual HR/ACM values to eliminate the inaccuracy of the estimation model. R was 0.9, R^2 value was 0.81, and SEE was 341 ml/min (10.7%, 4.78 ml/kg/min, which was divided by the average BM of the cross-validation group in the former grouping). In later grouping, the estimation model with the experimental group had an R of 0.86, an R^2 of 0.74, and a SEE of 358 ml/min (11.7%, 5.14 ml/kg/min, divided by the mean BM of the experimental group in the later grouping). The estimation model with the cross-validation group showed R = 0.85, R^2 = 0.72, and SEE = 437 ml/min (14.1%, 6.24 ml/kg/min, divided by the mean BM of the cross-validation group in the later grouping). If the estimation model was developed using only HR/ACM, R^2 was 0.71 and SEE was 374 ml/min (12.2%, 5.37 ml/kg/min, divided by the mean BM of the experimental group in the later grouping). The authors concluded that this study was the first accurate and reliable study of fitness estimation during daily life without any protocol. The model's reliability should be considered when applying it to other individuals with a different activity pattern or activity level.

Tonis et al. recently developed an accelerometer- and HR sensor-based VO_2max estimation model with walking exercise at two different speeds. The participants were 23 men and 18 women aged 20-29 years. The authors used the relationship between HR and the intensity of physical activity (by accelerometer) at different walking speeds. VO_2max was measured using a submaximal single-stage treadmill walking test. The accelerometer was attached to the waist belt, and seven ECG electrodes were attached to the chest and back. Activity intensity was calculated using the sum of the integrals of the absolute value of each axis of the accelerometer every 10 seconds.

A simple linear regression of acceleration and HR during walking exercise at 4 km/h and 5.5 km/h was developed for each individual. The fitness indices were the slope and intercept. The correlation coefficient between VO_2max and the fitness indices was -0.32 (slope) and -0.45 (intercept). Age, gender, weight, length, BMI, and the slope and intercept of the linear regression were used to develop the estimation model. The correlation coefficient of the measured VO_2max and estimation model with gender, intercept, and slope was 0.9, and the SEE was 2.052 ml/kg/min. Another estimation model with age, gender, intercept, and slope had R = 0.9 and SEE = 2.074 ml/kg/min. The limitation of the study was the young age and high fitness levels of the participants (83).

1.4 WHY CPF IS STILL UNPOPULAR

There are numerous methods of CPF measurement; however, these methods are not easy to repeat because of the need for professional judgment and specific protocols or equipment. Moreover, although exercise testing is generally safe, myocardial infarction or arrhythmias occur in up to 5 per 10000 tests, and sudden cardiac death occurs to 0.5 per 10000 tests (22). Simple, reliable, safe and practical measurement (or estimation) is required to check CPF.

1.4.1 DRAWBACKS OF MAXIMAL EXERCISE TESTING

CPF measurement with maximal exercise testing with ventilation gas analysis is the most precise and reliable method and is preferred in clinics and sports. However, the test is very expensive and requires professional equipment with appropriate space and the presence of cardiac experts (21, 22, 26). Moreover, individuals who perform maximal exercise tests must have a strong motivation to test (21, 26, 84). Although the direct measurement of VO_2max with a maximal exercise test is preferred, elderly or ill participants have to avoid maximal effort because of the risk of adverse cardiac events. Qualified medical supervision and emergency equipment should be available (85).

1.4.2 DRAWBACKS OF SUBMAXIMAL EXERCISE TESTING

Submaximal exercise testing could be an alternative because it obviates the drawbacks of maximal exercise testing, such as the need for professional expertise and participant motivation. However, it is not easy to select submaximal tests that are appropriate for participants' characteristics. The test should carefully replicate the reported equipment or environment to achieve reliable results (21). When appropriate tests are selected, they should be conducted more than once to overcome familiarization error because submaximal tests have learning effects. Cycle ergometer tests show little learning effect among the test modalities (21, 26, 86, 87).

Although submaximal tests have lower risks than maximal tests, their use among high-risk groups should be carefully approached. Prescreening is required, and physician should have concerns if the patient has any medication or health issues. Some submaximal exercise tests use maximal walking or running distance in an assigned time to estimate VO_2max. These methods could have inherent subtle differences because the test do not consider running economy, nutritional status, glycolytic capacity, running surface, wind resistance, and volitional capacity (21, 88, 89).

1.4.3 DRAWBACKS OF NON-PROTOCOL BASED TESTS

Non-protocol based CPF estimation basically uses physical activity to estimate CPF. However, subjective physical activity determination by self-reported questionnaire could under- or overestimate an individual's activity status (90). Objective measurements of physical activity with a pedometer could not discriminate the intensity or amount of physical activity; thus, they could be inaccurate for estimating CPF (75, 79).

Because the original idea of submaximal exercise tests is to use the linear relationship between oxygen uptake and mechanical power output and/or HR, several studies have used accelerometers and HR monitors to estimate CPF. However, two previous studies (81, 83) also used exercise protocols to estimate CPF, and genuinely protocol-free CPF estimation (82, 91) is impractical in daily life because of the long measurement duration and the discomfort of wearing accelerometer and HR equipment.

1.5 OBJECT OF THE THESIS

CPF has been proven to be strongly related to health status. Individuals understandably want to know their CPF to determine their health status. Sedentary people are likely to have a low level of CPF and to want to improve it. Structured exercise or additional physical activity in daily life can significantly improve CPF. It has also been proven that an increased CPF can decrease the risk of all-cause and CVD mortality.

Many previous studies have insisted that CPF should be assessed because of its influence on mortality (17, 24, 39). CPF is a stronger predictor of mortality than other widely known factors (hypertension, smoking status, diabetes, inactivity, cholesterol, and obesity) in both healthy individuals and CVD patients (18, 39). Clinicians should also use CPF together with other factors to assess and classify patients, thereby allowing clinical recommendations for physical fitness alterations (24).

Although individuals and clinicians want to ascertain CPF, there are no simple and practical methods for doing so. Maximal exercise tests are the gold standard, but they are difficult to perform because they require specialized, expensive equipment, professional expertise, and physically burdensome exercise. Submaximal tests also require special protocols and equipment and existent familiarity problems. Non-protocol tests could have estimation errors when determining activity levels via questionnaire (90). According to the definition of CPF, the circulatory and respiratory systems' responses to sustained physical activity must be determined. Some previous non-protocol tests use HR and accelerometers to measure physical activity; however, these are impractical because they require many measurement days and because the equipment is not appropriate for daily life. There is no simple and practical method of estimating CPF. The lack of interest in using CPF, in contrast to other risk factors (smoking, obesity, high blood pressure and high blood glucose) may arise from the difficulties in measuring CPF.

In this thesis, a novel CPF estimation algorithm without any specific exercise protocol was proposed and validated. This algorithm is based on the principle of submaximal testing with a linear relationship between oxygen uptake, HR, and objectively determined mechanical power output. Using objectively measured physical activity rather than self-reported physical activity may provide less-biased data on the association between habitual physical activity and the risk of mortality.

2. MATERIAL & METHODS

2.1 PARTICIPANTS

Thirty healthy Asian men without any diseases related to the cardiovascular system voluntarily participated in the study. All of the participants had sedentary occupations: 22 were graduate students, 7 were undergraduate students and 1 was an engineer. Among the participants, 7 were excluded from the final results for the following reasons: sensor error (3 participants), arrhythmia (1 participant), and failure in the maximal exercise test (3 participants). Therefore, twenty-three participants were included in this study. Detailed information about the participants is shown in table 1. The participants completed comprehensive health evaluations that included self-reported personal medical history related to cardiovascular disease, and they were given explanations of the study and signed written informed consent forms. This study was approved by the IRB of the National Medical Center in South Korea (IRB No. M-12111001-001).

Table 1 Characteristics of the included participants

	Mean ± STD
N	23
Age (years)	26.7 ± 5.8
Height (cm)	173.3 ± 6.5
Weight (kg)	71.8 ± 10.7
Bruce protocol duration (sec)	826.4 ± 96.1
Measured VO_2max (ml/kg/min)	47.9 ± 5.0
Whole measurement duration (min)	3069 ± 684
Smoking participants (subjects)	5
Resting HR (BPM)	85.4 ± 10.6
Measured maximum HR during maximal exercise test (BPM)	190.1 ± 7.4 *
Estimated maximum HR determined by age (220 − age) (BPM)	193.3 ± 5.8 *
Regularly exercising participants (N)	11

* Two values were not different ($p > 0.05$)

2.2 MEASUREMENT OF VO_2MAX

Ventilation gas was directly measured and analyzed using a metabolic cart (Vmax Encore System, CareFusion, San Diego, USA). The cart can measure flow and volume with 3% error. O_2 gas was analyzed by electro-chemical cell type sensors with a measurement range of 0% to 100% with 0.01% resolution. The CO_2 gas sensor was a non-dispersed infrared thermopile. It could measure a range between 0% and 16% with 0.01% resolution. Both sensors had only 0.02% inaccuracy. The metabolic cart also measured methane (CH_4) and acetylene (C_2H_2), which were not used to analyze VO_2max. All of the participants breathed only through the mouth using a mask over their mouth and nose during exercise. Ventilation gas was transferred to the metabolic cart and analyzed to determine the ratio of O_2 to CO_2 consumption.

The exercise protocol was performed with an aerobic exercise test system (CASE v6.61, GE Healthcare, Little Chalfont, United Kingdom). The system was composed of a treadmill, a twelve-lead electrocardiogram (ECG), and oxygen saturation (SpO_2) and blood pressure monitors. The treadmill gradually starts and stops for safe and smooth operation to accurately measure blood pressure even at high workloads. It also stops immediately when the emergency stop button is pressed.

Figure 5 Participant with experimental set up during maximal exercise testing (ECG, Blood Pressure, SpO_2, and Ventilation Gas Analysis)

2.2.1 PROTOCOL OF MAXIMAL EXERCISE TEST

The baseline physiologic parameters (ECG, resting HR, blood pressure, SpO_2, volume of oxygen consumption and CO_2 exhalation, and respiratory quotient) were measured with the subject in a standing position on the treadmill during five minutes of rest using all of the necessary devices. ECG was measured with a standard twelve-lead instrument. SpO_2 was measured on the forefinger of the right hand. The blood pressure cuff was worn on the left upper arm. The participant's nose was blocked with a small piece of cotton and covered with a mask that was connected to the metabolic cart via a hollow tube.

In this experiment, the modified Bruce protocol (23) was used to find the reference value for VO_2max. After the baseline measurement, a warm-up stage (treadmill speed) persisted for 1-2 min. The exercise session was initiated, and the treadmill's velocity and slope angle were changed every three minutes according to the protocol. VO_2max was determined when one of four determinations was achieved: the participant's respiratory exchange ratio was above 1.08; VO_2 did not increase along with increased work load; volitional fatigue indicated that the subject could not continue the test (20, 92), or the physician decided that the participant should not continue the test anymore because of excessive blood pressure or HR. After the exercise session, patients were followed during a 5-min recovery session.

Table 2 Speed and slope condition for the warm-up, modified Bruce protocol, and recovery session

	Speed (km/h)	**Slope (%)**
Warm-up	1.6	0
Exercise Stage 1	2.7	10
Exercise Stage 2	4.0	12
Exercise Stage 3	5.4	14
Exercise Stage 4	6.7	16
Exercise Stage 5	8.0	18
Exercise Stage 6	8.8	20
Exercise Stage 7	9.6	22
Recovery	2.4	0

2.3 ACCELEROMETER AND ECG SENSOR

The participants wore a Shimmer sensor (93) on the chest (Shimmer platform with ECG sensor module, Shimmer, Dublin, Ireland). The sensor consisted of an ECG and accelerometer. The gain of the ECG sensor was 175, and the frequency range was 0.05 Hz to 159 Hz. Leads II and III could be measured with the driven right leg. The Shimmer platform also contained an MMA7361 (Freescale semiconductor, Austin, Texas, USA) tri-axis accelerometer, which can be modified to a sensitivity of either 1.5 g or 6 g. The dimension of the Shimmer platform is 53 * 32 * 23 mm, and its weight is 32 g.

It can measure proper acceleration including gravitational acceleration. Accelerometer output is ranged from -1g to 1g according to axis alignment with gravity axis at stable position. When the sensor is moved with acceleration, sensor output is fluctuated according to induced acceleration and it can be over than 1g.

Sensor output can be amplified according to sensitivity of accelerometer. The sensitivity of the acceleration signal was set to 1.5 g. Ideally, an accelerometer-based physical activity monitor should be placed close to the center of body mass (8), but the sensor was placed on the chest to make it more comfortable during measurement. The X, Y, and Z axes corresponded to the longitudinal axis, the mediolateral to left axis, and the posterior-anterior axis, respectively.

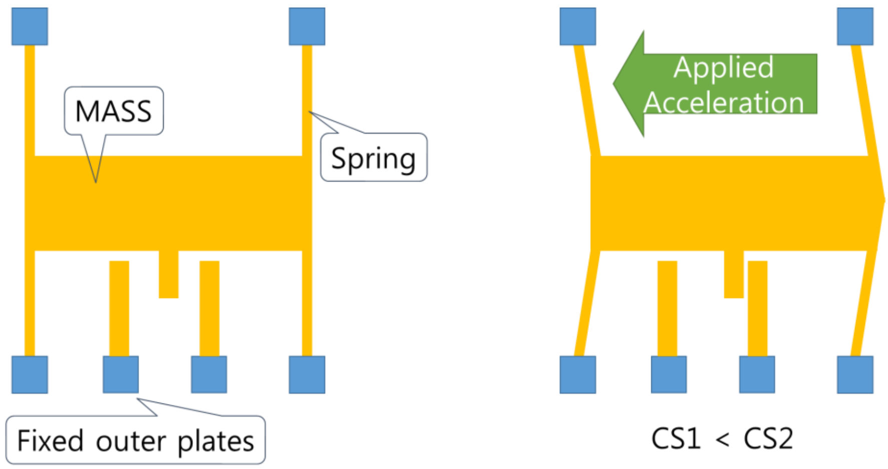

Figure 6 Principle of accelerometer. Charging electron is varied when acceleration applied to mass.

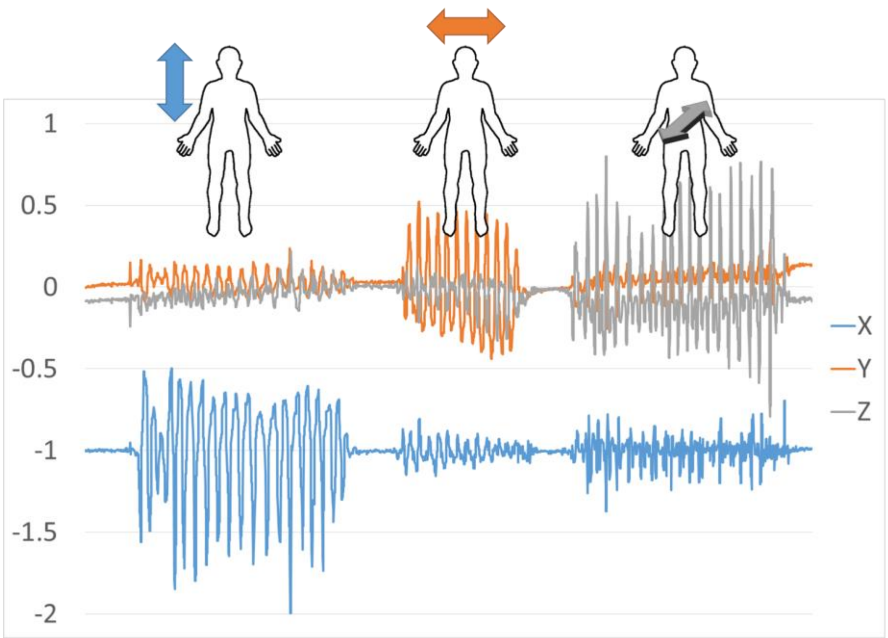

Figure 7 Accelerations according to axis of body movements.

All signal data were saved on a micro-SD card with a 51.2-Hz sampling frequency. The sampling frequency was appropriate to measure physical activity (9) but was relatively lower than the standard ECG frequency (94). The sampling frequency was selected to reduce battery consumption without losing signal quality to obtain R-R intervals (93).

The sensor was attached to the chest with an elastic chest belt. An ECG was obtained on the left chest near the left nipple with a hydrogel Ag/AgCl electrode (2223, 3M, Maplewood, Minnesota, USA) with a 10-cm-sized square-shaped placement. There were no inappropriate reactions, such as skin rash. An electrode was not placed on the general ECG lead position because the sensor needed to be comfortable for the participant and not disrupt daily life activities.

2.4 DAILY LIFE MEASUREMENTS

According to a previous study, which determined that a minimal reliable duration of energy expenditure for accelerometer testing is 3.5 days (8), ECG Lead II and III and 3-axis acceleration were recorded over four consecutive days during daily life. The participants removed the sensor during sleep or showering and replaced the ECG electrodes to reattach the sensor after completing those activities. The saved data were extracted two times, 48 hours and 96 hours after initiating measurement. All of the participants performed maximal exercise testing during the 4-day daily life activity measurement.

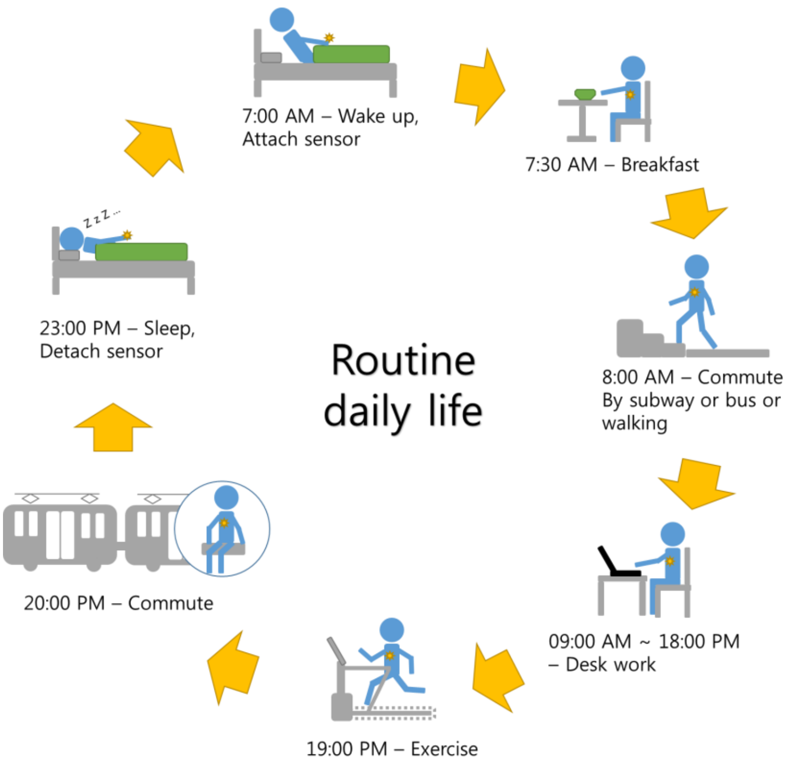

Figure 8 Example of routine daily life

2.5 SIGNAL PROCESSING

Whole data were reviewed, and if the ECG was inaccurate because of electrode contact problems or sensor detachment, the matching accelerometer data and ECG data were removed. The tri-axis acceleration was band-pass filtered (0.25 to 7 Hz, 2nd order). Filtered acceleration was rectified and integrated into every minute to obtain the acceleration count per minute (ACM). Body mass, gender, and horizontal and vertical ACM were used to obtain the activity energy expenditure (aEE) using a non-linear model. The correlation coefficient between indirect calorimetry and the accelerometer was 0.866 on normal days and 0.939 on the exercise day (9, 12).

Equation 2 Equations for activity energy expenditure (aEE) estimation from (12)

$$aEE = a_N \times {ACM_{horizontal}}^{p_1} + b_N \times {ACM_{vertical}}^{p_2}$$

$$p_1 = \frac{2.66 \times \ body\ weight\ (kg) + 146.72}{1000}$$

$$p_2 = \frac{-3.85 \ \times \ body\ weight\ (kg) + 968.28}{1000}$$

$$a_N = \frac{12.81 \ \times \ body\ weight\ (kg) + 843.22}{1000}$$

$$b_N = \frac{38.90 \ \times \ body\ weight\ (kg) - 682.44 \ \times \ gender + 692.5}{1000}$$

$$, where\ gender = 1\ in\ male, 2\ in\ female$$

$$ACM_{horizontal} = \sqrt{\left(\int |accelerometer_y|\right)^2 + \left(\int |accelerometer_z|\right)^2}$$

$$ACM_{vertical} = \int |accelerometer_x|$$

The HR was calculated from ECG lead II and band-pass filtered (5 to 20 Hz, 4nd order). The R peak detection algorithm of Pan and Tompkins (95) was modified and used to get RR intervals; each of the R-R intervals was averaged for one minute and converted to an HR (beat per minute). Because previous research showed that the recovery HR after physical activity was heterogeneous (96) and less correlated with VO_2max (97), we used only the increased HR section because of physical activity. To use only the increasing HR period, the raw HR data were smoothed, and an inclusion period was selected during which an increase in HR lasted for at least 4 minutes. After the smoothed HR increase period was selected, the raw HR was used to calculate the aEE and HR relationship.

A simple linear regression equation was developed using HR and aEE. Maximum aEE (aEEmax) was estimated with the maximal HR determined from the participant’s age (220 − age). To define the optimal measurement duration, the aEEmax was compared with the measured VO_2max according to the time duration of measurement.

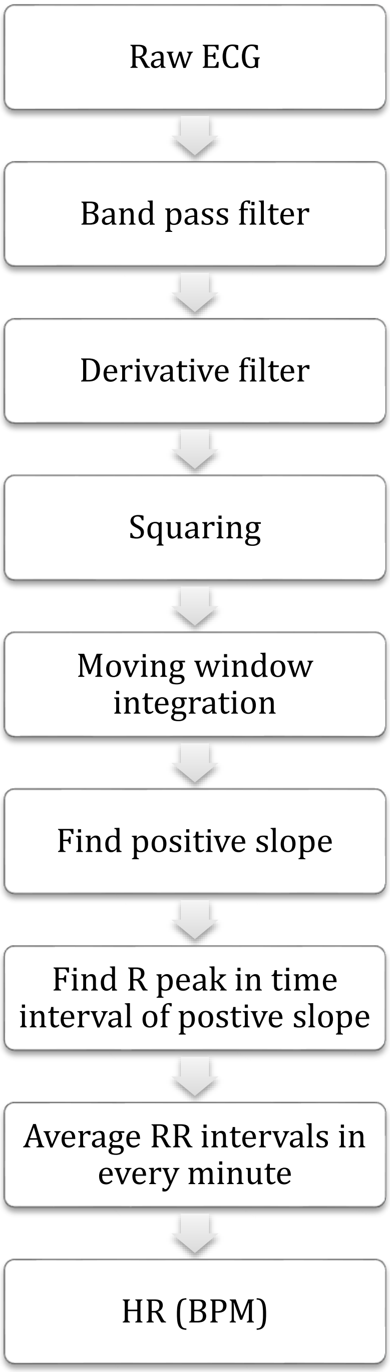

Figure 9 ECG Signal processing procedure to get HR in bpm

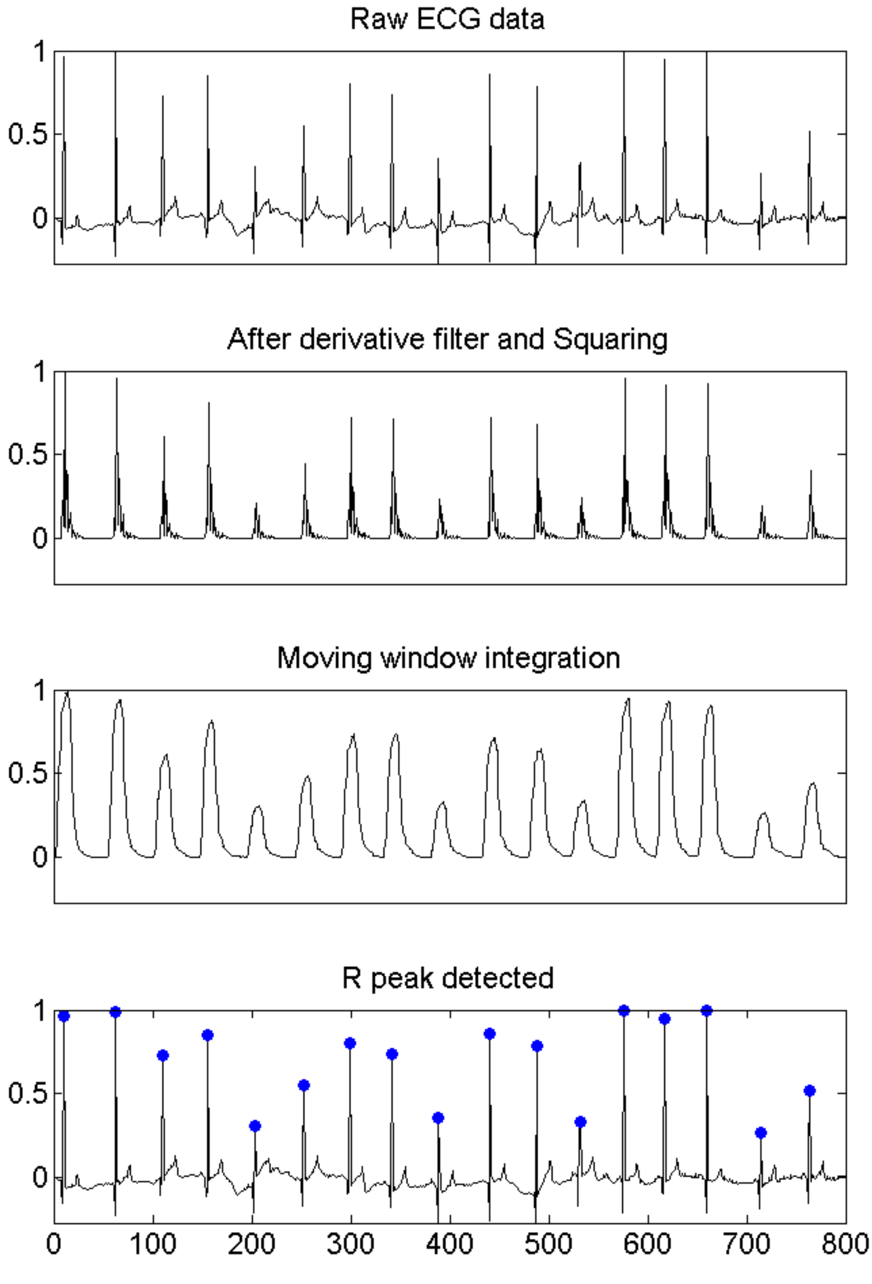

Figure 10 ECG R peak detection by modified Pan-Tompkins algorithm (95)

2.6 MULTIPLE LINEAR REGRESSION

After the aEEmax calculation, all of the participants were divided into two subgroups according to aEEmax. The test group included every third participant along the ascending sorted aEEmax, and the training group included the others. The number of participants in training group was 15; the test group included 8 participants. The aEEmax and anthropometric value were used to develop a multiple linear regression model to estimate the VO_2max in the training group's data, and the values were cross-validated using the model with the test group's data.

2.7 STATISTICS

Pearson's correlation coefficient was used to evaluate the agreement of aEEmax and the measured VO_2max value in both groups. A two-sided p value less than 0.05 was regarded as significant. Regression equations were evaluated by coefficients of determination (adjusted R^2), absolute SEE and relative SEE (%SEE). A Bland-Altman plot was created to determine the difference between the measured and estimated VO_2max. All signal processing, cross validation, and statistical analysis was performed using MATLAB (MATLAB2014a, Mathworks, Natick, Massachusetts, USA).

3. RESULTS

3.1 GROUP CHARACTERISTICS

Table 3 Participant characteristics of the training and test groups. The p value was calculated using the Mann–Whitney U test. No characteristic differed between the two groups.

	Training (n = 15)	Test (n = 8)	p
Age (years)	27.5 ±6.6	25.1 ±3.7	0.41
Height (cm)	172.6 ±6.8	174.8 ±6.2	0.72
Weight (kg)	70.1 ±11.2	75.0 ±9.6	0.27
The duration of the Bruce protocol exercise (sec)	842 ±89	796 ±107	0.27
Measured VO_2max (ml/kg/min)	48.5 ±5.3	46.8 ±4.5	0.28
The duration of ECG measurement sensor (min)	2935 ±767	3319 ±426	0.18

3.2 HR AND AEE CALCULATION

The graphs below show one participant's aEE (upper graph) and HR (lower graph) over time. Although the participant had more than 1000 min of recorded data, the figure shows only the first 730 min. The gray section under the HR curve represents the sections with increasing HR. When aEE increased, the associated HR increased.

The HR and aEE values for every minute during the increasing HR sections are shown in scatter plot. The solid line comes from a simple linear regression between HR and aEE. Many data points were on the lower level of HR and aEE; however, some of the data were dispersed along the regression line. The aEEmax was calculated by extrapolating the regression line to the maximum HR (determined by individual's age). The aEEmax is a virtual value and is used as fitness index to develop multiple regression.

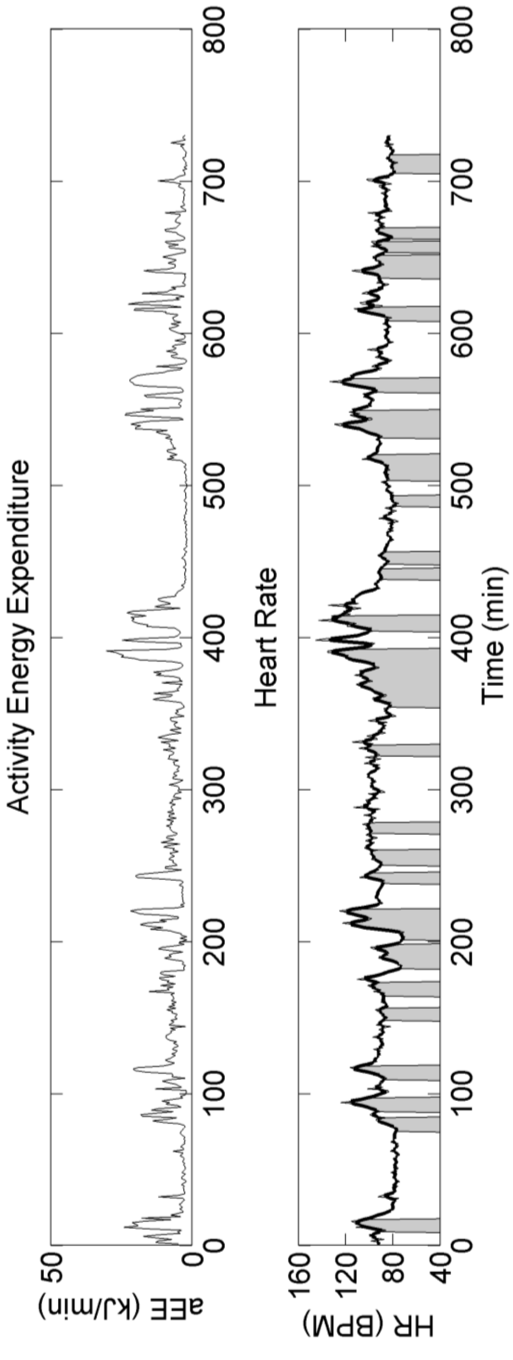

Figure 11 Example data of activity energy expenditure and heart rate along to time in one participant

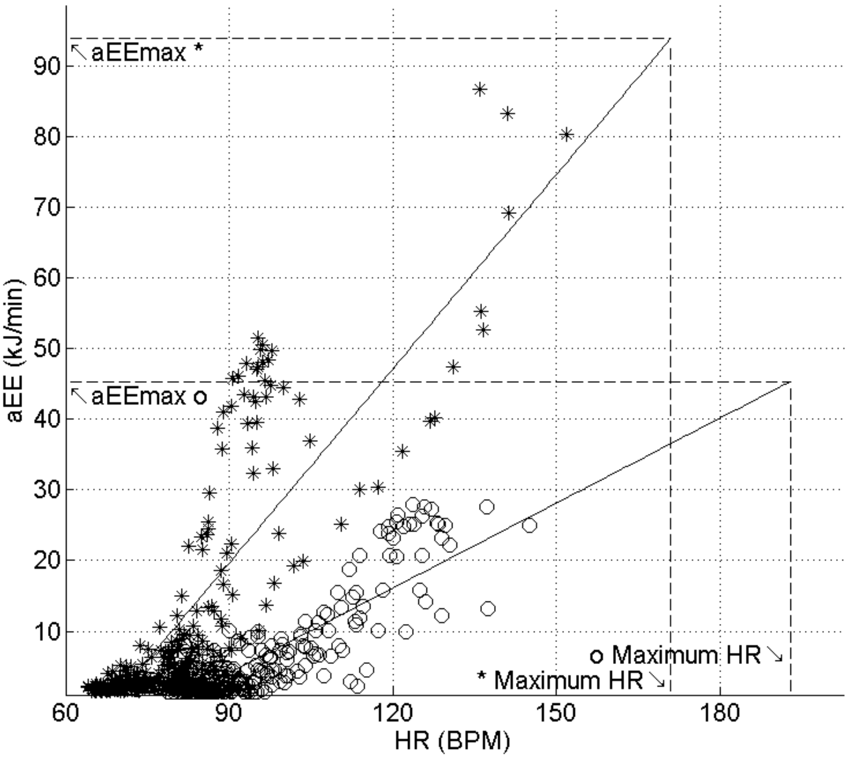

Figure 12 Comparison of two participants who has very different VO_2max.

Star mark represents fit participant's data and circle mark is unfit participant

3.3 CORRELATION COEFFICIENT

All correlation coefficients for the independent variables and the dependent variable (Measured VO_2max) are listed in Table 4. Weight, height, and BMI were negatively correlated with aEEmax ($p < 0.01$). Weight, BMI, and aEEmax were also significantly correlated with the measured VO_2max value ($p < 0.01$).

Table 4 Correlation coefficients

		Age	Weight	Height	BMI	aEEmax	Measured VO_2max
Age	R	1					
	p						
Weight	R	-0.10	1				
	p	0.641					
Height	R	-0.43*	0.66**	1			
	p	0.037	0.000				
BMI	R	0.11	0.881**	0.23	1		
	p	0.598	0.000	0.277			
aEEmax	R	0.16	-0.68**	-0.53**	-0.56**	1	
	p	0.447	0.000	0.007	0.005		
Measured VO_2max	R	-0.03	-0.62**	-0.30	-0.64**	0.86**	1
	p	0.871	0.001	0.154	0.001	0.000	

R: Correlation coefficient; *: $p < 0.05$; **: $p < 0.01$

3.3.1 INCLUDED DURATION OF DATA AND AEEMAX

Changes in the correlation coefficient between aEEmax and VO_2max occurred according to the included measurement duration of the aEEmax calculation. The correlation coefficient was 0.86 when only 730 minutes of HR and aEE data during daily life were used to calculate aEEmax. The correlation coefficient fluctuated but did not drastically increase when a longer measurement duration was used.

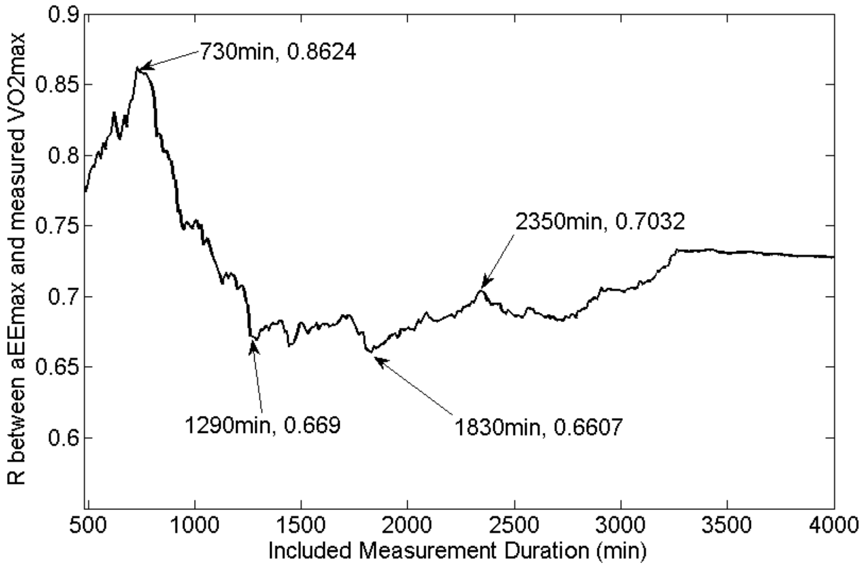

Figure 13 Correlation coefficient between aEEmax and measured VO_2max according to included time duration

3.4 PERFORMANCE OF REGRESSION EQUATION

The aEEmax and anthropometric value were used to develop a multiple linear regression model to estimate the VO_2max in the training group data and were cross-validated using the model with the test group data.

The regression formulas were expressed below. Four estimation model was developed and validated. Independent variable which were significantly related to measure VO_2max were selected to develop estimation model. Model 1 used aEEmax and constant to estimate VO_2max. Model 2 used aEEmax, weight, and constant. Model 3 used aEEmax, BMI, and constant. Model 4 used aEEmax, BMI, weight, and constant.

Equation 3 Estimation equation of model 1

$$\dot{V}O_2 \max \left({}^{ml}/_{min \times kg}\right) = 0.36 \times aEEmax \left({}^{kJ}/_{min}\right) + 25.75$$

Equation 4 Estimation equation of model 2

$$\dot{V}O_2 \max \left({}^{ml}/_{min \times kg}\right) = 0.29 \times aEEmax \left({}^{kJ}/_{min}\right) - 0.14 \times Weight\ (kg) + 39.53$$

Equation 5 Estimation equation of model 3

$$\dot{V}O_2 \max \left({}^{ml}/_{min \times kg}\right) = 0.28 \times aEEmax \left({}^{kJ}/_{min}\right) - 1.03 \times BMI \left({}^{kg}/_{m^2}\right) + 55.03$$

Equation 6 Estimation equation of model 4

$$\dot{V}O_2 \max \left({}^{ml}/_{min \times kg}\right) = 0.37 \times aEEmax \left({}^{kJ}/_{min}\right) - 2.01 \times BMI \left({}^{kg}/_{m^2}\right) + 0.39 \times Weight\ (kg) + 44.89$$

The estimated VO_2max was strongly correlated with the measured VO2max values of all models in both groups.

Table 5 Performance of multiple linear regression in both groups

		R	**p**	**Adjusted R^2**	**SEE (%)**
Model 1	Training	0.87	0.000	0.74	2.81 (5.59)
	Test	0.88	0.004	0.75	2.98 (6.37)
Model 2	Training	0.87	0.000	0.74	2.71 (5.59)
	Test	0.88	0.004	0.75	2.93 (6.25)
Model 3	Training	0.88	0.000	0.76	2.61 (5.37)
	Test	0.84	0.001	0.69	3.07 (6.55)
Model 4	Training	0.91	0.000	0.82	2.29 (4.73)
	Test	0.75	0.031	0.53	4.84 (10.34)

R: Correlation coefficient; R^2: Coefficient of determinant; SEE: Standard error of the estimate (ml/min/kg); aEEmax: Maximum activity energy expenditure

3.4.1 COMPARISON OF MEASURED AND ESTIMATED VO_2MAX

The correlation between the estimated and measured VO_2max value was determined for all subjects. The thin line is the identity line, and the thick line is the regression line of the measured and estimated VO_2max.

Distributions of all subjects were little differed, however correlation coefficients were similar with each other. Correlation coefficient of training group were 0.87 – 0.91 and of test group were 0.75 – 0.88.

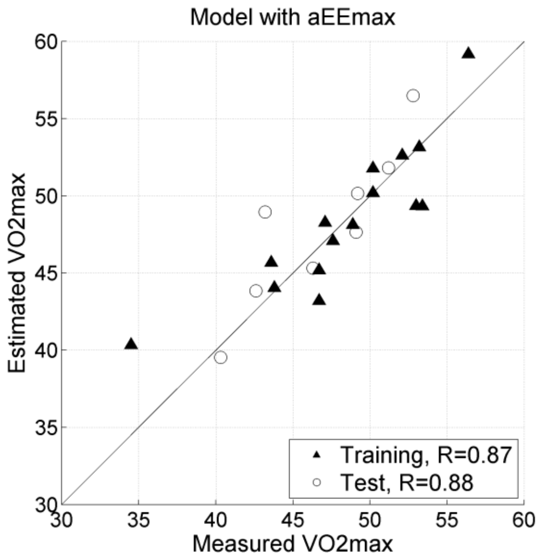

Figure 14 Comparison between measured and estimated VO_2max in model 1

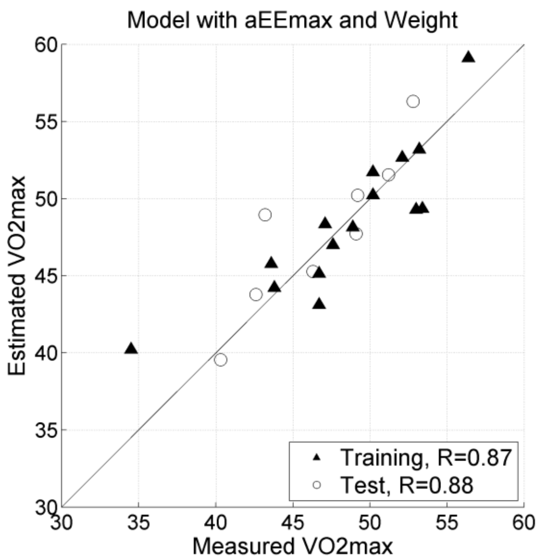

Figure 15 Comparison between measured and estimated VO_2max in model 2

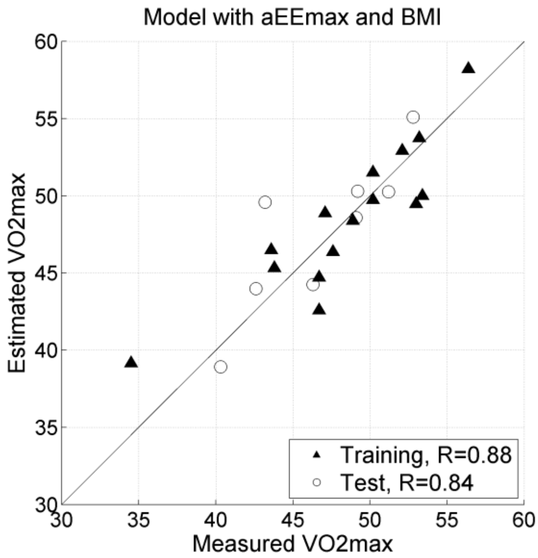

Figure 16 Comparison between measured and estimated VO_2max in model 3

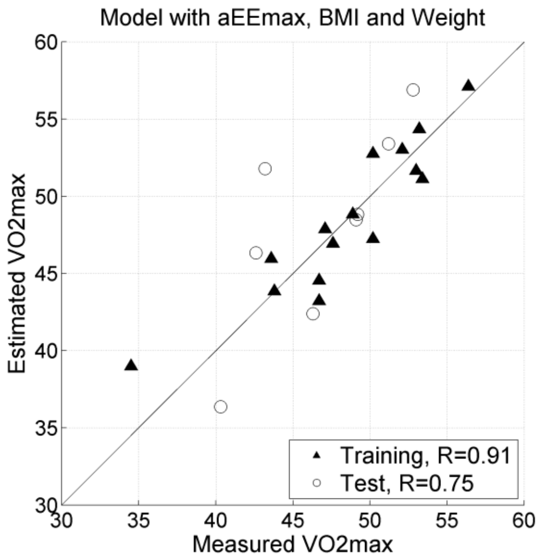

Figure 17 Comparison between measured and estimated VO_2max in model 4

3.4.2 BLAND–ALTMAN PLOT

X axis is average of estimated and measured VO_2max, y axis is difference between estimated and measure VO_2max (measured VO_2max subtracted from estimated VO_2max). The solid line is the mean value, and the dashed line represents the 1.96 standard deviation (95% limits of agreement). Every subject was randomly dispersed in the 1.96 STD range except one participant. The mean difference (95% limits of agreement) between the measured and estimated VO_2max was shown below. Mean and STD were similar with each other models. All of mean values were positive that estimation models were average 0.27 – 0.43 (ml/kg/min) over estimated than measured VO_2max value.

Table 6 Mean and 95% range of difference between estimated and measured VO_2max.

	Mean	**STD**	**95% Range**
Model 1	0.39	5.04	-9.48, 10.27
Model 2	0.38	5.00	-9.44. 10.19
Model 3	0.27	5.00	-9.52, 10.10
Model 4	0.43	5.98	-11.30, 12.15

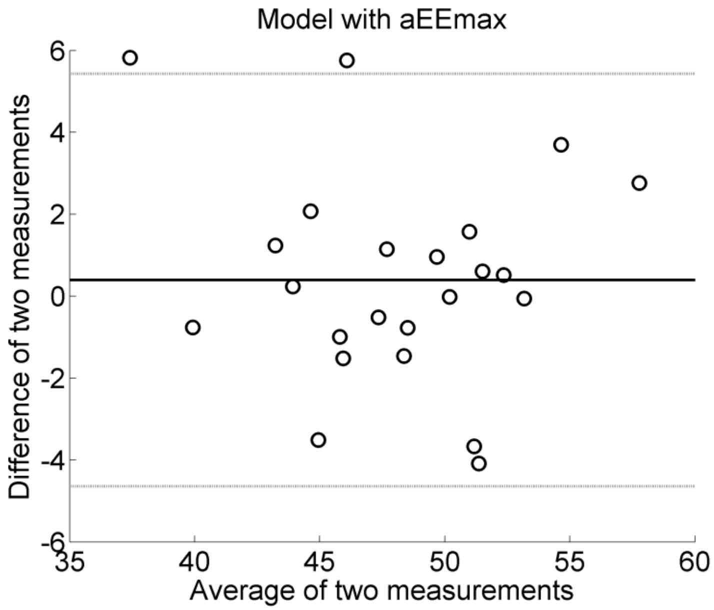

Figure 18 Bland-Altman plot of model 1

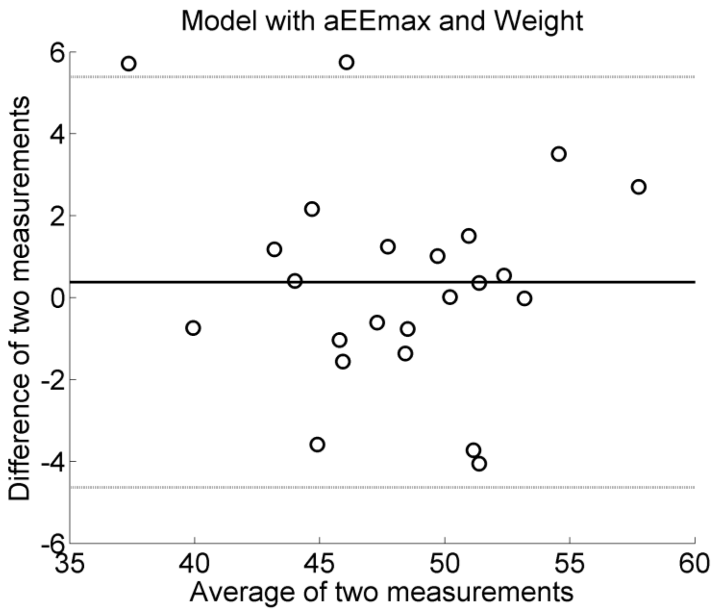

Figure 19 Bland-Altman plot of model 2

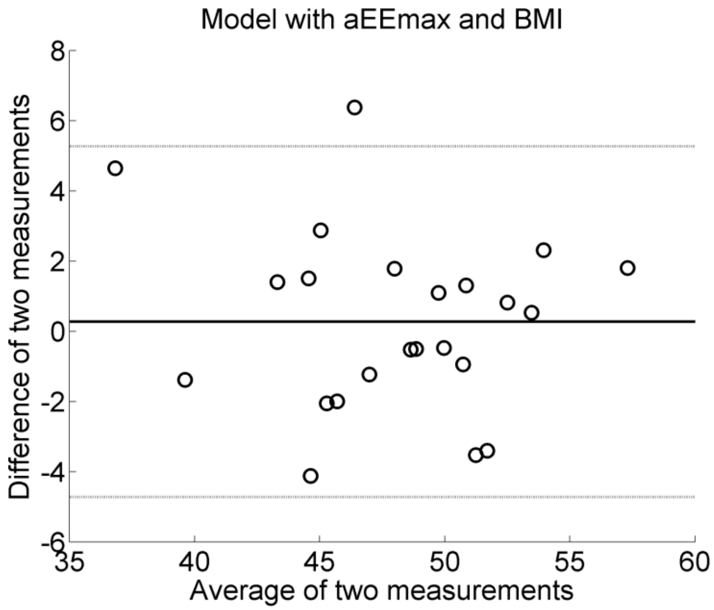

Figure 20 Bland-Altman plot of model 3

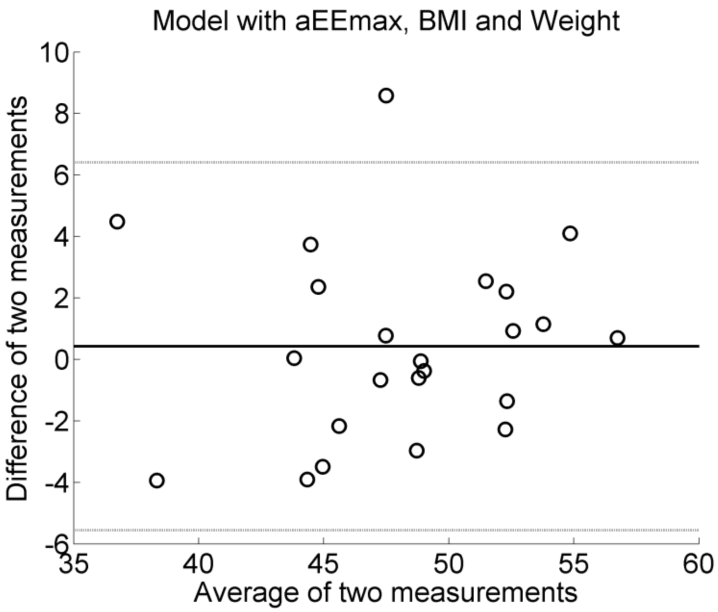

Figure 21 Bland-Altman plot of model 4

3.4.3 AVERAGE COMPARISON OF ESTIMATED AND MEASURED VO_2MAX

Average of estimated and measured VO_2max were compared by t-test and not differed respectively. Mean value of measured VO_2max is 46.93 and each models' estimated VO_2max were listed in table 7.

Figures in this section show the comparison between estimated and measured VO_2max using a box plot. Points are drawn as outliers if they were larger than q3 + 1.5 * (q3 – q1) or smaller than q1 – 1.5 * (q3 – q1), where q1 and q3 are the 25th and 75th percentiles, respectively. This represents approximately ±2.7 STD and 99.3 coverage if the data are normally distributed.

Table 7 Comparison of quartile values between estimated and measured VO_2max. P value is calculated from t-test comparison between estimated and measured VO_2max value.

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Measured VO_2max**
Upper	59.17	59.11	58.21	57.10	56.4
75%	51.38	51.22	50.59	52.51	51.7
Median	48.25	48.34	48.88	48.49	48.3
25%	45.21	45.17	44.85	44.89	43.7
Lower	39.54	39.56	38.92	36.36	34.5
Mean	48.31	48.29	48.19	48.34	46.93
p	0.47	0.49	0.61	0.51	

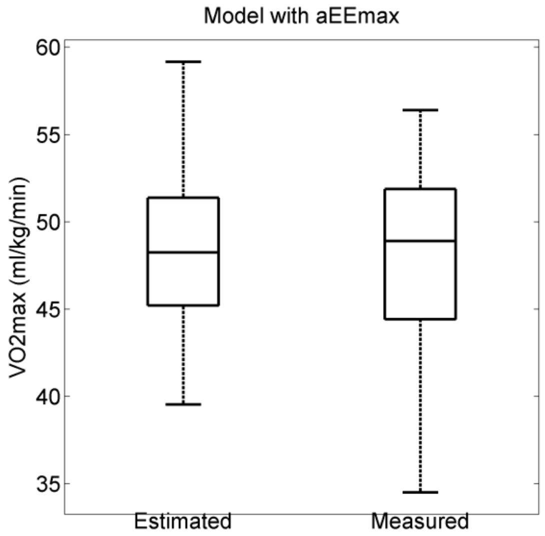

Figure 22 Box plot for distribution comparison in model 1

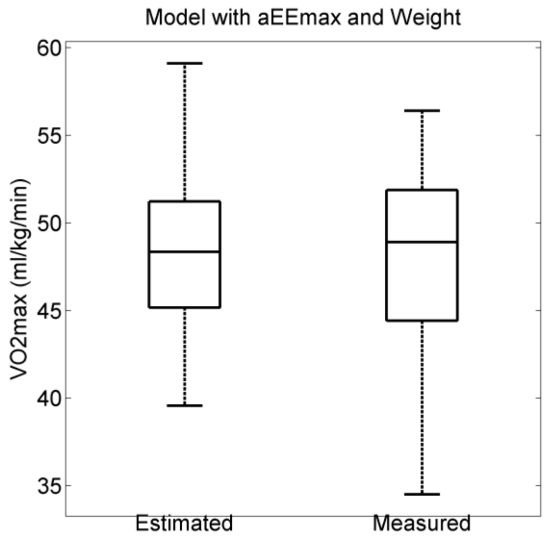

Figure 23 Box plot for distribution comparison in model 2

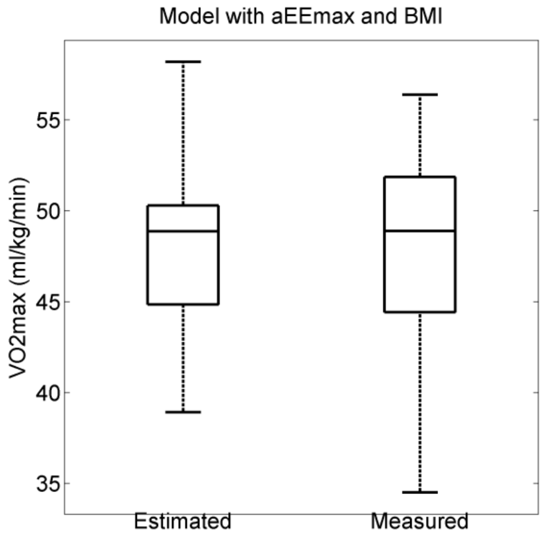

Figure 24 Box plot for distribution comparison in model 3

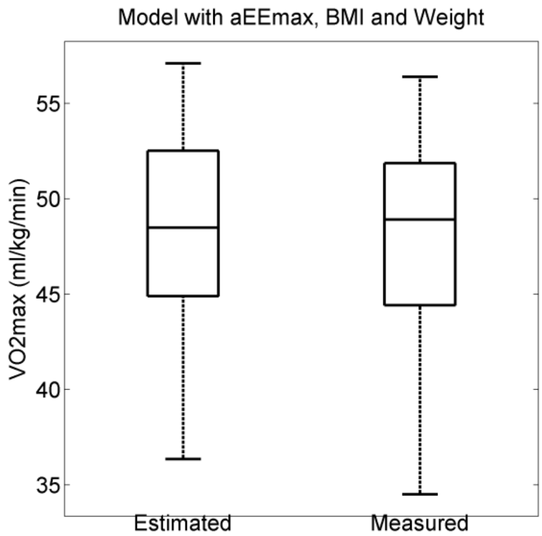

Figure 25 Box plot for distribution comparison in model 4

4. DISCUSSION

4.1 SUMMARY

This study developed a VO_2max estimation model based on the relationship between physical activity (aEEmax) and physical response (HR) using a combined ECG and tri-axis accelerometer in sedentary young and healthy individuals. The strong correlation between the physical activity index and CPF in this study was consistent with the findings of previous studies (72, 79, 80, 82). The VO_2max estimation using a linear regression model with aEEmax and anthropometric factor was highly correlated with the measured VO_2max in both the training group and the test group. Four models were all good in estimation; model 3 and 4 were better than model 1 or 2. Actually estimation model 4 using aEEmax, weight, BMI, and constant, weight was overlapping in model because of BMI. Thus, best estimation model was model 3, which uses aEEmax, BMI, and constant. It shows high correlation coefficient ($R = 0.88$ and 0.84, in training and test group respectively), and also high in adjusted coefficient of determinant ($R^2 = 0.76$ and 0.69, in training and test group respectively).

4.2 REASON FOR INCREASSING HR SELECTION

4.2.1 CORRELATION BETWEEN HR RECOVERY AND VO_2MAX

HR recovery from physical activity has been found to be heterogeneous (96) and not strongly correlated with VO_2max (97). The authors of these studies investigated the effects of short-term exercise and recovery and found that VO_2max did not correlate with heart rate recovery after the all-out 30 s test ($R = 0.16$, $p = 0.69$). Thus, physical activity index (aEEmax) was calculated with only increasing HR to estimate VO_2max.

4.2.2 REMOVE PSEUDO ACTIVITY ENERGY EXPENDITURE

Activity energy expenditure was calculated by acceleration which was measured on the participant's chest. Accelerometer measures any change of acceleration regardless of acceleration source. Therefore, large acceleration could be measured even sit position when participant take vehicles. These large acceleration was also converted to pseudo large aEE during signal processing. According to preliminary experiment which is not reported in this thesis, aEE during sit on driving bus could be 2.77 to 3.71 times higher than aEE during stable sit position on the ground. However, the HR was not increased during both situation due to physical inactivity.

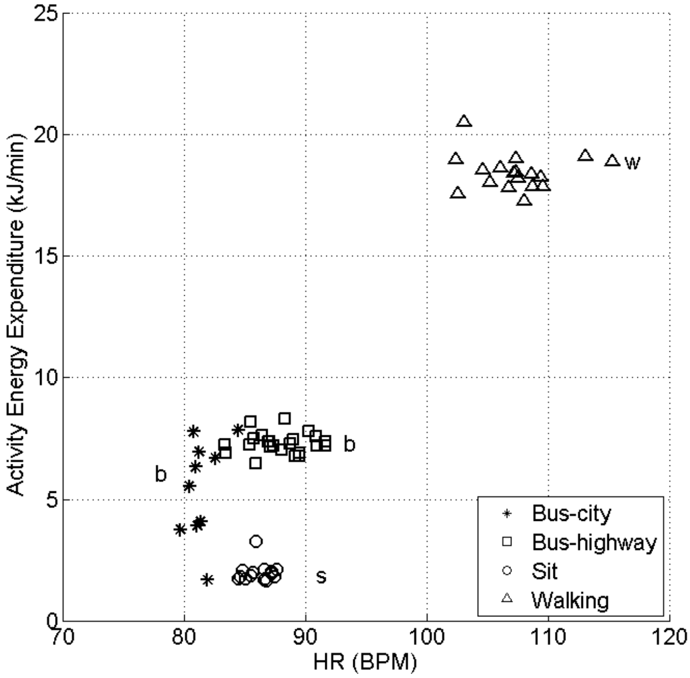

Figure 26 Activity energy expenditure comparison among participant's status. Triangle mark is shown measured data during walking, others were measured during stable sit (on the bus or stable sit position)

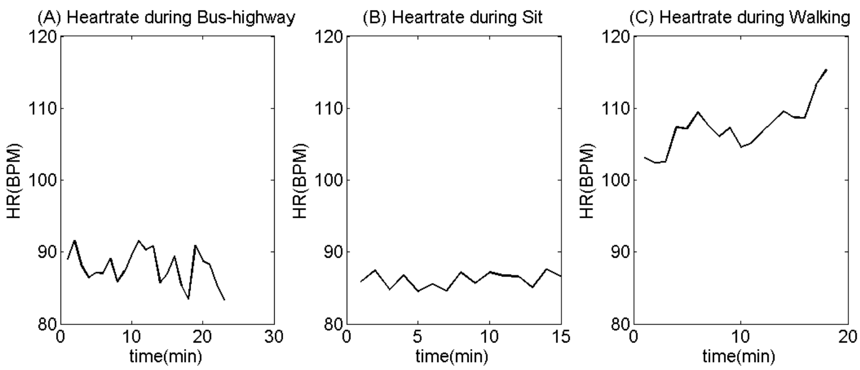

Figure 27 Comparison of heart rate during stable sit position (A: on the bus, B: stable sit) and walking (C)

When large pseudo aEE associated with low HR were used in aEEmax calculation, aEEmax could be overestimated than real aEEmax which was calculated by only physical activity induced acceleration data. For the purpose of filter out pseudo acceleration, aEEmax should be calculated with only HR increasing section; because continuous large acceleration with HR increasing is only originated from sustained physical activity. Therefore, HR increasing selection method could exclude pseudo acceleration data with low HR.

4.2.3 REMOVE PSEUDO HEART RATE INCREASING REGARDLESS OF PHYSICAL ACTIVITY

Heart rate is normally between 60 to 100 beats per minute. HR could be changed according to change of physical or psychological status. When air temperature is increased, HR is slightly increased (up to 10 BPM) due to pump more blood. HR could be also increased according to change of body posture. HR is increased right after 15 – 20 seconds of stood up and settled down after couple of minutes. Moreover, anxious or unusual extreme emotions could make HR increased. However, these pseudo HR increasing situation will not affect to CPF estimation. HR increasing factors are not affect to HR more than several minutes and are not affect steady increasing.

4.2.4 SIMILAR PRINCIPLE WITH MAXIMAL INCREMENTAL EXERCISE TEST

Golden standard of VO_2max is maximal exercise test. Bruce protocol, one of famous maximal exercise test, is incremental test to extract maximum physical exertion to get maximal oxygen consumption. HR and aEE could be continuously increased during Bruce protocol test. According to unreported HR and aEE data which attained during Bruce protocol, continuous increasing HR and aEE were shown. The aEEmax was calculated using the data during Bruce protocol and showed strong correlation with measured VO_2max value ($R = 0.71$, $p = 0.002$).

During daily activity, however, it is hard to achieve continuous increasing HR and aEE which were similar with maximal exercise test. To imitating continuous increasing situation during maximal exercise test, HR increasing time interval was only selected to estimate VO2max; because continuous increasing of aEE was hardly occurred during daily activity.

4.3 WHY HR SHOULD BE USED AS AN INCLUSION CRITERION RATHER THAN AEE

We had to use HR as a period selection criterion rather than aEE because of individual differences in the absolute intensity of physical activity. If the included data had been determined by aEE, we would have chosen high intensity aEE rather than an optimized aEE threshold for each individual. However, a high intensity of aEE can differ among the participants and should not be generalized from normal to ill or elderly individuals.

Moreover, accelerometer detects any acceleration induced to sensor regardless of source of acceleration, aEE could be error if participant were inside of subway or car or elevator in daily life. Because vehicle induced acceleration can also calculated as aEE of participant. Although there was no actual physical activity in individual, false positive body acceleration induces false positive aEE. HR was not increased at false positive aEE and that data could degrade estimation model.

Therefore, certain proportion of an individual's vigorous physical activity mainly induces continuative HR increments during daily life. HR can be increased by emotions or heat; however, such increases would not frequently occur and would not continue over several minutes in normal daily life.

4.4 MEASUREMENT DURATION

We theoretically assumed that 4 consecutive days would be necessary to detect accurate aEE in adults (8). As the results demonstrate, however, the aEEmax calculation with only 10 hours of measurement data was significantly correlated with the VO_2max (600 min, $R = 0.81$, $p < 0.01$). We concluded that for the purpose of achieving a more robust correlation coefficient to estimate VO_2max, only 12 hours (730 min) of measurement, instead of 4 days, was sufficient to reveal the relationship between aEEmax and VO2max.

4.5 HR AND AEE FOR CALCULATING AEEMAX

4.5.1 SIMPLE LINEAR REGRESSION

A simple linear regression similar to the YMCA estimation method (98) was used to calculate aEEmax. aEEmax was more strongly correlated with measured VO_2max than any other correlation coefficient of any previous fitness index that used HR and physical activity (present method: $R = 0.74$, Plasqui et al: $R = -0.48$ (91), Tonis et al: $R = -0.45$ (83)).

4.5.2 VARIABLE ASSIGNMENT

There were two variables (HR and aEE) and two methods of variable assignment in simple linear regression to calculate aEEmax. The aEEmax value could be varied according to variable assignment in linear regression. According to the statistical principle that known value is assigned to x variable and unknown value (or estimating value) should be assigned to y variable, HR was assigned to x variable and aEE was assigned to y variable.

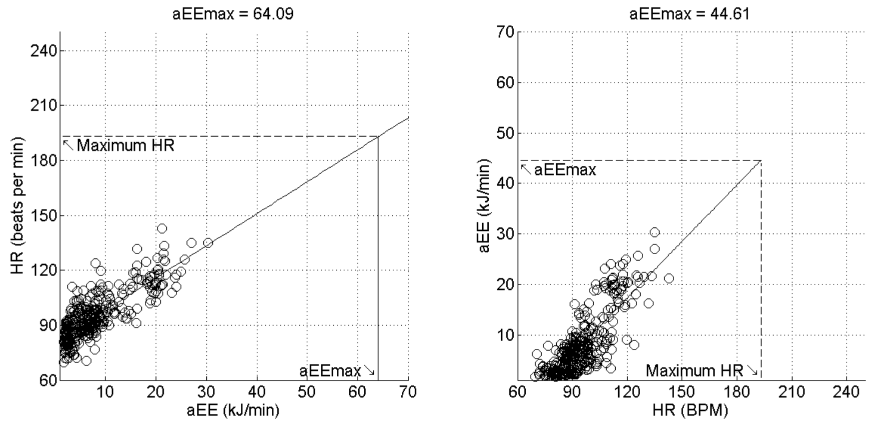

Figure 28 Change of aEEmax according to variable assignment in linear regression

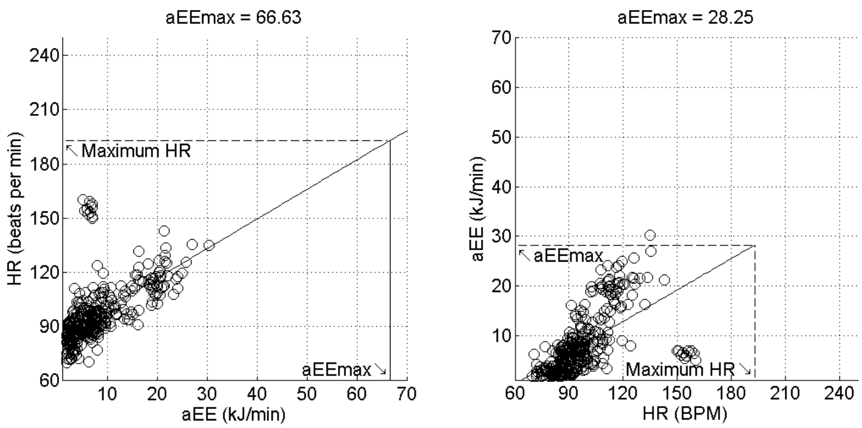

Figure 29 Change of aEEmax when dummy data was inserted

To determine this variable assignment is proper, dummy data was inserted to a participant's measured data. When aEE was assigned to x variable and HR was assigned to y variable, aEEmax was estimated to 64.09. If variable switched each other, aEEmax was estimated to 44.61 and it is true because the maximum HR was known value. When low fitness dummy data (high HR associated with low aEE) were inserted to measured data, aEEmax should be lowered because aEEmax is positively correlate to measured VO2max. When dummy data was inserted to proper variable assignment (x: HR, y: aEE) regression model, aEEmax was lowered. However, aEEmax was increased when same dummy data was inserted to improper variable assignment (x: aEE, y: HR) regression model. According to this result, HR should assigned to x variable and aEE assigned to y variable in calculation of aEEmax.

4.5.3 SYNCHRONIZATION OF HR WITH ACTIVITY ENERGY EXPENDITURE

Physical activity induces HR increasing. Within one second after the beginning of muscle contraction, HR and heart contraction force is increased by stimulated sympathetic nervous system (98). Time synchronization of HR with aEE should consider the sub-second time delay between physical activity and increasing HR. However, the calculation of aEE and HR was averaged in one minute (measurement unit of aEE was kJ per min and HR was beats per min), time delay between aEE and HR was already considered in data synchronization. If aEE was synchronized with delayed HR, aEE could be associated with HR at one minute after; because minimal time epoch was one minute. When HR data in time T_i was associated with aEE data in time T_i, R between aEEmax and VO_2max was 0.8 – 0.9 according to models. However, R was 0.5 – 0.7 when HR data in time T_{i+1} was associated with aEE data in time T_i. Synchronization of aEE with delayed HR was not appropriate in this algorithm, however, time delayed synchronization could be helpful if time epoch is set to several seconds.

4.6 PREVIOUS STUDIES USING OBJECTIVE PHYSICAL ACTIVITY AND HR TO ESTIMATE VO_2MAX

Various CPF estimation methods using indices of physical activity and physical response have been reported (81-83, 91). However, Weyand et al. and Tonis et al. needed specific protocols to estimate VO_2max. To the best of my knowledge, there was only one group who intended to estimate CPF without any protocol. Plasqui et al. reported a VO_2max estimation method that used anthropometric values, HR, and acceleration data collected over 7 consecutive days (82). The average of HR divided by acceleration count was negatively correlated with VO_2max, and a multiple linear regression model was developed. After that study, a cross-validation study was also conducted to establish a more robust regression model (R = 0.86 - 0.90, R^2 = 0.71 - 0.74, SSE = 341 - 437 ml/min) (91). Despite the good performance of the estimation, the weakest point regarding adapting the algorithm is the need for 7 measurement days. The separate attachment of an HR sensor and accelerometer could also make the subjects uncomfortable and cause behavior changes. The unified sensor system used in this study appears to be less obtrusive than that used in previous studies. Sartor et al. indicate that the future of non-protocol VO_2max estimation requires unobtrusive devices and assessments that are based on only 1 day of activities or even a single physical activity (21).

4.7 ADVANTAGE OF THE METHOD

Presented method improves upon previous non-protocol VO_2max estimation methods in two ways. First, our method requires only 13 hours of measurement, which is shorter than in all previous studies. We believe that the time advantage would originate from the selection of increasing HR period, aEEmax determination by age, and unified HR with an accelerometer sensor. Despite the actual measurement time comprising one or two days because of differences in activity type (as well as sleeping time and water-related activities), it may be possible to estimate the VO_2max using daily life activity data from only one day (21). Second, the performance of the estimation regression model in this study was comparable to that of previous reports, despite the much shorter measurement duration.

4.8 LIMITATION

4.8.1 PARTICIPANTS

The number of participants was not large, and the participants were homogeneous. Because all of the participants were young, healthy Asian men with sedentary occupations, the generalization of the regression model requires further validation studies in larger populations of various ages, races, sexes, and health statuses. Although men show clearer trends in the correlation between mortality (41) and change in CPF (44), more participant variety is need to adapt the algorithm to participant characteristics (e.g., females, the elderly, children or low fitness patients).

4.8.2 CALCULATION OF ACTIVITY ENERGY EXPENDITURE

The error rate will increase when participants perform static exercise, which can raise the HR with low-activity energy expenditure or anaerobic exercises. Although the total energy expenditure was not proven to be better for VO_2max than for aEE, a more robust algorithm could measure both activity energy expenditure and static energy expenditure by combining an accelerometer with heat-flux-based energy expenditure measured on skin (5).

4.9 SUGGESTION OF PATCH TYPE SENSOR FOR CPF MEASUREMENT

Plasqui et al. (91) reported that combined activity monitor and HR sensor could improve wearing comfort and result high accuracy. In this thesis, although the conventional unified aEE and HR sensor was attached to participant's left chest by elastic strap, it could be still uncomfortable because of chest belt and thick sensor. Moreover, the sensor was not specialized to measure CPF. Considering these concerns of sensor issue, more light and comfort CPF sensor is necessary to get reliable data; patch type wearable sensors could be most appropriate type of new CPF sensor.

4.9.1 REQUIREMENTS OF CPF SENSOR

For the purpose of CPF estimation, patch type sensor should measure vibration or movement of body and electrical biosignals induced by physical and physiological activity.

Vibration could be measured by MEMS chip type accelerometer as same as conventional method, it could be also measured by ferroelectret film. Although MEMS type accelerometer is small and thin (usually 4 * 4 * 2 mm sized), ferroelectret film is thinner (up to 100um) and more flexible which can securely attach the film to skin contour.

Conventional ferroelectret film needs metal electrode on both sides of film to read out charging electron when the film is compressed; it was major obstacle to apply the sensor to wearable deivce. To overcome the lack of flexibility in metal electrode, conductive ink or tape type electrode formation on both sides of film could be used. Electrodes were connected to high-sensitivity I-V converter to measure charged electrons. Output voltage should be filtered and amplified to get body movement signals.

Moreover, these flexible electrodes could be also worked as electrodes for measuring electrical biosignals. Formation of multiple electrodes on film capacitate ferroelectret sensor to multipurpose bio-signal acquisition sensor platform. Additional electrodes could be used as sensor for heat-flux based total energy expenditure or ECG measurement.

When this multipurpose sensor platform were applied to measure CPF, vibration of physical activity and associated ECG could be simultaneously measured at one spot of human body. These two signals was most important to estimate CPF because CPF is circulatory and respiratory systems' ability to supply fuel during sustained physical activity.

4.9.2 IMPLEMENTATION OF PROTOTYPE SENSOR

Prototype of CPF sensor were implemented and tested the feasibility and reliability. All electrodes were formed by conductive tape on electromechanical film (Emfit ferroelectret film, Emfit, Finland). Three electrodes were on front side and the other one was on back side. Film with electrodes was attached to one side of printed circuit board (PCB) which has I-V converter, instrumentation amp, filters, main controller unit for analog to digital converter and wireless transfer. Although flexible PCB is more appropriate to this sensor platform, prototype was composed by non-flexible PCB. The size of sensor was 85 * 55 * 8 mm which is as same size as credit card.

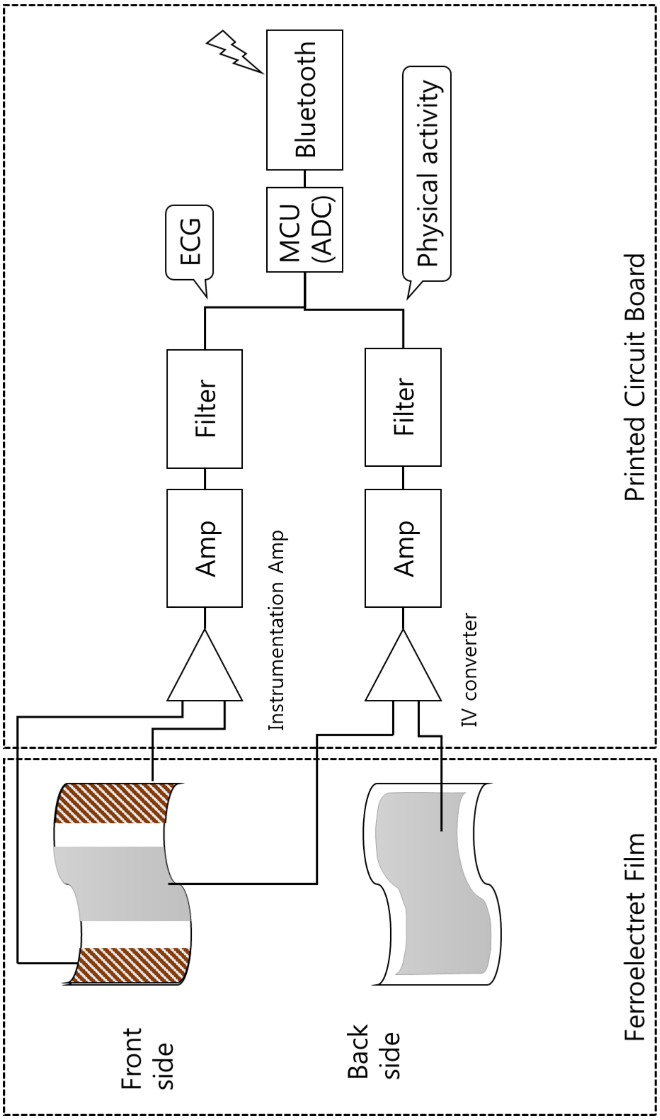

Figure 30 Schematic of prototype sensor

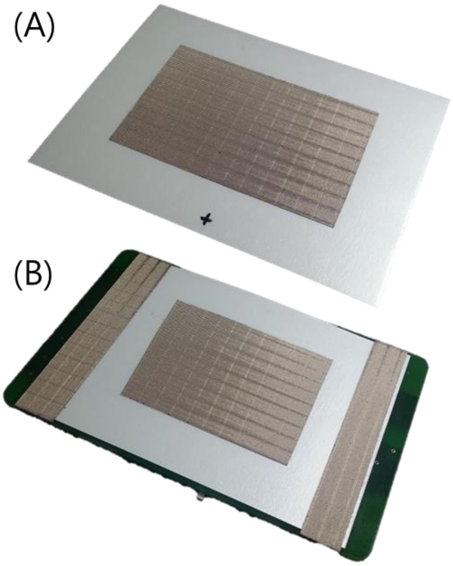

Figure 31 (A) Backside of film (B) Combined PCB and film (front-side view of film)

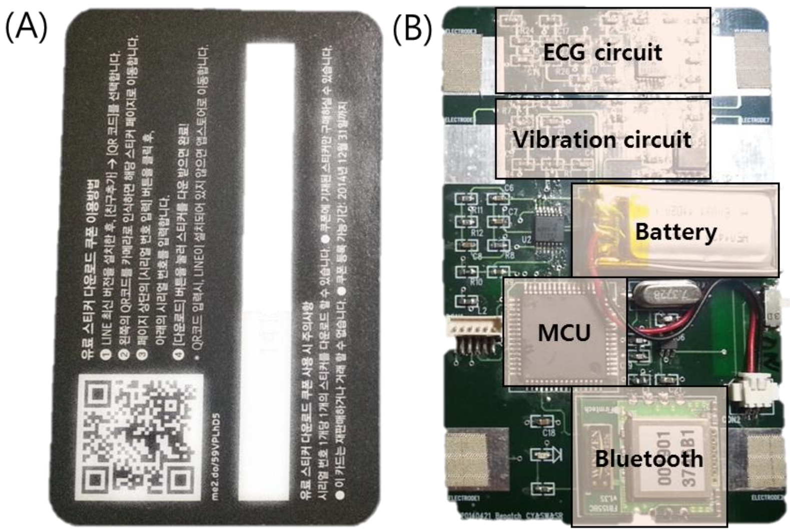

Figure 32 (A) Comparison of size with credit card (B) prototype of CPF sensor, printed circuit board with electronic parts

4.9.3 FEASIBILITY TEST OF SIGNAL ACQUISITION

ECG and physical activity signals were acquired and compared between stable and walking using the prototype CPF sensor. Sensor platform transfer acquired data to PC program (Labview 2013, National Instruments, NI) via Bluetooth (FB155bc-smd, Firmtech, South Korea). Sampling rate was 1200 samples per second. Gathered data were filtered (5 to 40 Hz) and plotted in MATLAB (MATLAB 2014a, Mathworks, USA). Filtering cutoff frequency was relatively higher than previous experiments because ECG electrode was dry capacitive type electrode. ECG data was noisier than Ag/AgCl electrode and easy to be affected by motion artifacts.

Because the experiment was not approved by IRB, the author attached the sensor to left chest as same as previous experiment. The sensor was covered by medical adhesive film (OPSITE, Smith&Nephew, UK). ECG and activity levels were measured during standing and walking situation. R peak of ECG signals could be clearly distinguished in both situation. Activity level was low at stable standing, however, the amount of activity level was increased at walking.

Although aEEmax and VO_2max value was not calculated, it was revealed that the biosignals from the prototype CPF sensor was appropriate to measure ECG R peaks and distinguished activity level. In the further study, clinical trials should be followed with optimize CPF sensor and the CPF estimation algorithm should be modified according to signal characteristics of the sensor.

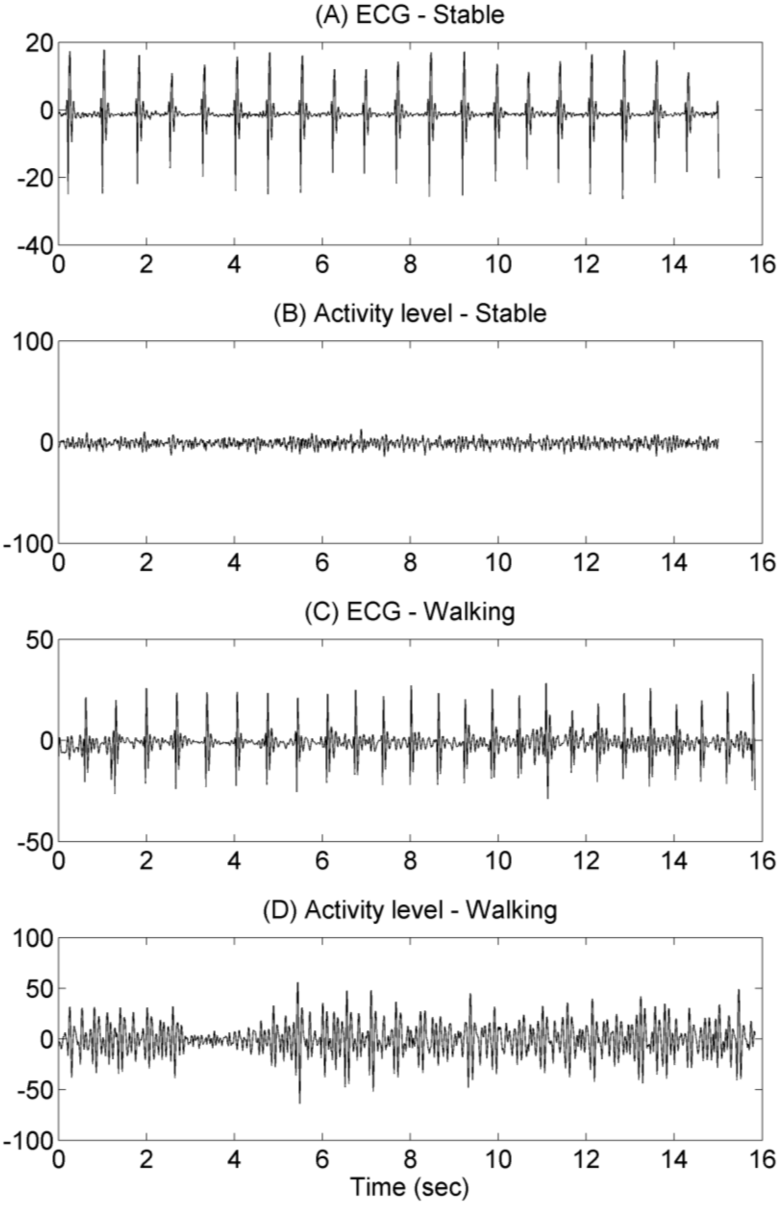

Figure 33 Comparison of signals acquired by prototype CPF sensor. (A) ECG, (B) activity level at stable stand posture, (C) ECG, (D) and activity level during walking. RR interval was clearly shown and activity level duing walking was increased than stable standing.

4.10 FURTHER STUDY

4.10.1 FOLLOW-UP STUDY

A follow-up study is needed to verify whether the estimation model can detect changes in physical fitness after regular aerobic exercise (34). Moreover, Stamatakis et al. developed a reliable nonprotocol estimation model (with 14650 men and 17669 women aged 35-70 years) and found a mortality trend using the model in a follow-up study (99). The model tested in the present study could be used to reveal mortality in a long-term study.

4.10.2 SENSOR MODIFICATION

Various accelerometer conditions (accelerometer type, sensitivity, and position on body) (7, 8), the adaptation of appropriate algorithms to participants' characteristics (6, 8), and the detection of estimation errors that increase HR via static anaerobic exercise, emotional responses, or heat should be studied more deeply to improve measurement accuracy.

Estimation performance can be improved by other aEE and HR measurement methods. Photoplethysmography or ballistocardiogram could replace ECG for HR measurement. Accelerometer-based physical activity could also be replaced by or upgraded with other methods with proven reliability. For the purpose of screening CPF, the developed algorithm could be applied to a commercially available activity tracker or prototype CPF sensor to measure activity and HR despite its low accuracy for estimating CPF.

5. CONCLUSIONS

Despite the importance of cardiopulmonary fitness, no practical method exists to estimate maximum oxygen uptake without a specific exercise protocol. The present study is the first report on a VO_2max estimation model using a short period (12 hours) without any exercise protocol (21).

The maximum oxygen uptake of 23 healthy, sedentary men was measured by using the maximal exercise test. Corresponding heart rate and activity energy expenditure data were also recorded. The maximum activity energy expenditure was estimated by age, using the first 12 hours of aEE, and HR data recorded from 4 days of typical daily life. Participants were divided into training (n = 16) and test (n = 7) groups, according to aEE, and a regression model for estimating maximum oxygen uptake was developed. The aEE estimated from 12 hours of daily living correlated significantly with the measured maximum oxygen uptake value, and recording beyond 12 hours did not improve the estimation. In addition, the estimated maximum oxygen uptake agreed with the measured maximum oxygen uptake value.

Despite the short measurement duration, the accuracy of the model is good compared with previous non-protocol VO_2max estimation studies. The method is unobtrusive and allows simple measurements because the HR sensor and accelerometer are both present in the same unit. This combined sensor and VO_2max estimation model could be helpful for determining VO_2max without the use of a professional protocol or other specialized equipment. Estimated CPF can be used to check health status and guide appropriate physical activity according to individual fitness levels.

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7. 요약 (국문 초록)

심폐 체력은 건강 관련 체력 지표 중의 하나로 동작중인 근육에 산소를 공급하는 역량을 의미하며, 심폐 체력의 증진은 체계화된 운동의 주요 목표이다. 심폐 체력은 전체 사망률 및 심혈관계 관련 사망률과 밀접한 연관이 있고, 심폐 체력의 증가는 사망률을 낮춘다는 것이 알려져 있다. 심폐 체력의 증가와 사망률간 음의 상관관계가 있기 때문에 심폐 체력은 건강 관리에 있어서 중요한 요소임에도 불구하고 적절한 관심을 받지 못하는 이유중의 하나는 심폐 체력을 실용적이면서 믿을만하게 측정 할 방법이 없기 때문이다.

심폐 체력을 나타내는 지표는 일반적으로 최대 산소 섭취량 (VO2max)이 있고, 표준화된 측정법으로는 최대 운동 부하 검사 (Maximal Exercise Test) 를 수행하면서 호흡하는 가스를 분석하는 방법을 사용한다. 그러나 이는 체력적으로 매우 힘이 들기 때문에 피험자가 측정을 하고자 하는 강력한 동기를 갖고 있어야 하며, 환자나 고위험군 사용자는 측정이 어렵고, 고가의 실험 장비와 인력을 필요로 한다. 반면, 최대하 운동 부하 검사법 (Sub-maximal Exercise Test) 은 상대적으로 쉬운 운동 프로토콜을 따르며 측정을 하지만 피험자에 적합한 프로토콜을 선정하는 것이 결과에 큰 영향을 끼치고, 검사 시 수행하는 운동 방법의 친숙도에 의해서도 결과가 영향을 받는다. 운동 프로토콜 없이 개인의 운동량이나 신체 정보를 이용하여 최대 산소 섭취량을 추정하는 방법들 (Non-exercise Estimation Method)은 운동량 측정의 부정확성, 오랜 측정 시간 (최소

7일 이상), 운동에 의한 인체의 반응을 측정하지 않는 점 등이 단점으로 알려져 있다.

최근에는 심폐 체력을 추정하기 위해 심박수와 운동량을 동시에 측정하여 분석하는 연구가 있었다. 심폐 체력이 좋은 사람은 그렇지 못한 사람에 비해서 같은 운동을 하더라도 심박수가 더 낮거나 천천히 증가할 것이라는 기본적인 원리에서 출발하였으며, 일상 생활 중의 데이터를 이용하거나, 특정 운동 프로토콜을 수행하면서 측정한 데이터를 이용한다. 이는 체력 부담이 적어서 고위험군 사용자에게 매우 좋은 방법이지만, 특정 운동 프로토콜을 필요로 한다는 점은 여전히 문제가 되며, 일상생활에서 측정하는 연구는 너무나 오랜 측정 시간 (7일)을 필요로 하여 실용성이 떨어진다.

이에 본 논문에서는 23명의 건강한 성인 남성을 대상으로 심폐체력 지표인 최대산소 섭취량을 추정할 수 있는 시스템과 알고리즘을 개발하고 검증하는 연구를 수행하고 그 결과를 정리하였다. 피험자는 최대 운동 부하 검사법을 이용해 개인별 최대 산소 섭취량을 측정하고, 4일 간의 일상 생활 중에 심박수와 운동량을 동시에 측정하였다. 측정한 심박수와 운동량으로부터 피트니스 인덱스 (aEEmax)를 계산하였고 이를 최대 산소 섭취량과 비교하였으며, 피트니스 인덱스와 개인별 신체 정보를 바탕으로 최대 산소 섭취량을 추정하는 회귀 모델을 수립하고 검증하였다.

피트니스 인덱스는 최대 산소 섭취량과 매우 강한 상관관계가 있었으며 ($R = 0.86$, $p = 0.000$), 4일간의 데이터 중에서 초기 730분의 데이터만을 사용하여도 최대 산소 섭취량을 추정하는데 충분하다는 점을 파악할 수 있었다. 향후 운동량 측정법을 개선하고, 측정의 편의성을 증대시켜서 추정 모델을 개선할 수 있으며, 본 연구를

통해 개인의 심폐체력을 손쉽게 측정할 수 있게 됨으로써 심폐체력 측정과 관리가 개인의 건강관리에서 매우 중요한 요소가 될 것이다.

주요어 : 피트니스, 심폐 체력, 최대 산소 섭취량, 활동 에너지 소모량, 회귀 분석

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