

WASO: Why Does It Increase with Age?

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Abstract

Insomnia is a common sleep disorder, especially for seniors. WASO (time awake after sleep onset), a component of insomnia, tends to increase with age. There are also many variations in WASO for seniors. To better understand the nature of insomnia, an equation was developed to predict WASO using maximum oxygen uptake (VO_{2max}) as a measure of fitness associated with aerobic exercise. Predictions from the equation matched measured values with an $R^2 = 0.98$. The results were highly significant ($p < 0.001$). A second equation was used to predict VO_{2max} as a function of age and relative fitness (a measure of aerobic fitness independent of age). The two equations were combined to predict WASO as a function of age, gender, and relative fitness. Based on these results, it appears that aerobic exercise to improve relative fitness can be used to reduce WASO. The WASO model explains the numerous reports of reduced WASO associated with long-term exercise programs. The model also explains why WASO increases with age and why high WASO values associate with early death.

Keywords

WASO, Time Awake, Sleep Disorders, Sleep Quality, Aerobic Exercise

1. Introduction

Insomnia is one of the most common sleeping disorders as people age [1] [2] [3]. Estimates range from 10 to 15 percent [2] to 35 percent [3] for general populations. For women only, 40 percent has been reported [3]. Walker (2017) [1] has discussed the two major components of insomnia: failure to go to sleep as measured by SOL (sleep onset latency) and failure to stay asleep as measured by WASO (time awake after sleep onset). The focus of this paper is WASO.

In addition to not feeling refreshed from sleep when WASO is high, high levels of WASO are associated with a protein, tau. Tau has been associated with an increased risk of developing Alzheimer's disease [1] [4]. Ju *et al.* [4] have re-

ported a link between Alzheimer's disease and two proteins, tau and amyloid- β . They relate the increase in tau to reduced and disturbed sleep. When WASO is high, the quantity and quality of sleep are often insufficient to purge tau from the brain during sleep [1]. They also relate the amyloid- β protein to the loss of slow-wave sleep. The decline of slow-wave sleep and the increase in WASO both occur as a person ages. One may not cause the other, but both may be a function of other variables that change with age, such as maximum oxygen uptake. There is little doubt that lack of sleep or loss of certain sleep components increases proteins in the brain that elevate the risk of developing Alzheimer's disease as a person ages. It appears that understanding the nature of WASO might be useful in understanding, evaluating, and reducing the risk of Alzheimer's disease.

Wallace *et al.* [5] reported that high WASO was associated with increased mortality risk.

Dolezal *et al.* [6] reviewed the literature from January 2013 to March 2017 relating sleep components including WASO to exercise. They reported that exercise is usually beneficial for sleep. They found that 29 out of 34 studies (85 percent) concluded that exercise improves sleep quality or duration. They also noted that exercise intervention showed the most robust results for middle-aged and elderly adults. Their final conclusion was that "sleep and exercise exert substantial positive effects on one another."

Eleven of the 34 studies measured WASO. In seven of these 11 studies, a decrease in WASO was reported in association with exercise. There were no reported increases. Types of exercise varied. Some studies reported exercise over a period of time suggesting an improvement in fitness. Measures of fitness, however, were usually lacking. Even with several studies in recent years, there appears to be no clear mathematical relationship between fitness and WASO.

Ohayon *et al.* [7] analyzed 66 sleep data sets and found that WASO increases at an increasing rate as people age. They used an exponential equation to predict the trend of the measured values. While there was much scatter in their results reported in graphical form, there is clear evidence that WASO increases at an increasing rate as people age. They did not include exercise or aerobic fitness as part of their analysis. Based on the more recent studies reporting WASO, it appears that exercise leading to improved fitness might be a missing variable in addition to age.

It seems clear that a mathematical model is needed in an attempt to explain both age and fitness effects on WASO. The objective of this present work is to develop a mathematical relationship that includes both age and aerobic fitness to predict WASO.

2. Methods

2.1. Connecting WASO to Maximum Oxygen Uptake

As a starting point, a measure of fitness is needed. One measure, VO_{2max} , integrates the performance of both heart and lungs [8] to provide oxygen to muscle

tissue and the brain. This variable increases with aerobic exercises, such as running, cycling, and swimming [8] [9]. After prolonged training of a couple of months at a constant intensity of aerobic exercise, VO_{2max} will plateau indicating a new steady-state level of aerobic fitness [9]. A detailed study by Saltin *et al.* [9] demonstrated that aerobic fitness as measured by VO_{2max} decreases during a period of bed rest and increases in response to increased aerobic exercise until a plateau is reached. Because VO_{2max} is a measure of heart and lung capacity, it should be a good measure of fitness both integrating and smoothing out the daily variations associated with exercise.

It is also known that VO_{2max} decreases as a person ages [8] [10] [11]. **Figure 1** illustrates the decline of aerobic fitness as a function of age for women. This data set also illustrates the effect of aerobic training on VO_{2max} . A similar relationship for men is shown in **Figure 2**.

The predicted values shown in each figure are from the following equation:

$$VO_{2max} = 107.4RF\left(1 - \frac{A}{120}\right) + G \tag{1}$$

where VO_{2max} = aerobic fitness ($ml \cdot kg^{-1} \cdot min^{-1}$)

RF = relative fitness (fraction of upper limit)

- (1.00) upper limit, Olympic class skier or runner
- (0.82) approximate upper limit for endurance training
- (0.67) endurance training
- (0.50) active (upper boundary for sedentary)

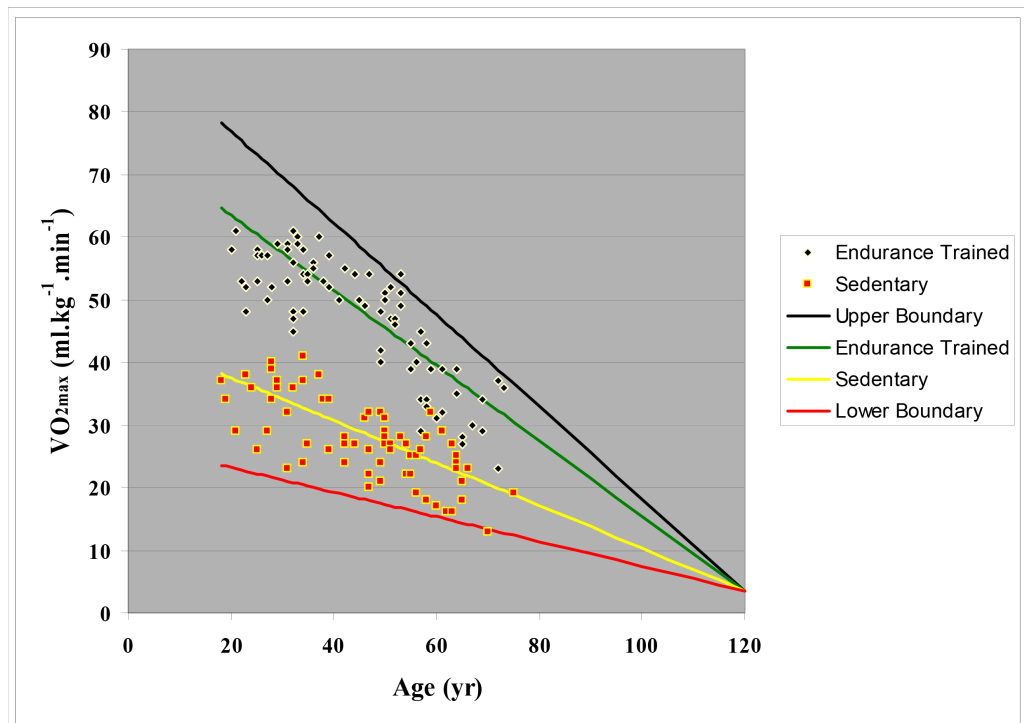


Figure 1. Reduction of VO_{2max} for women as a function of aging and fitness lifestyle. Data from Tanaka *et al.* [10].

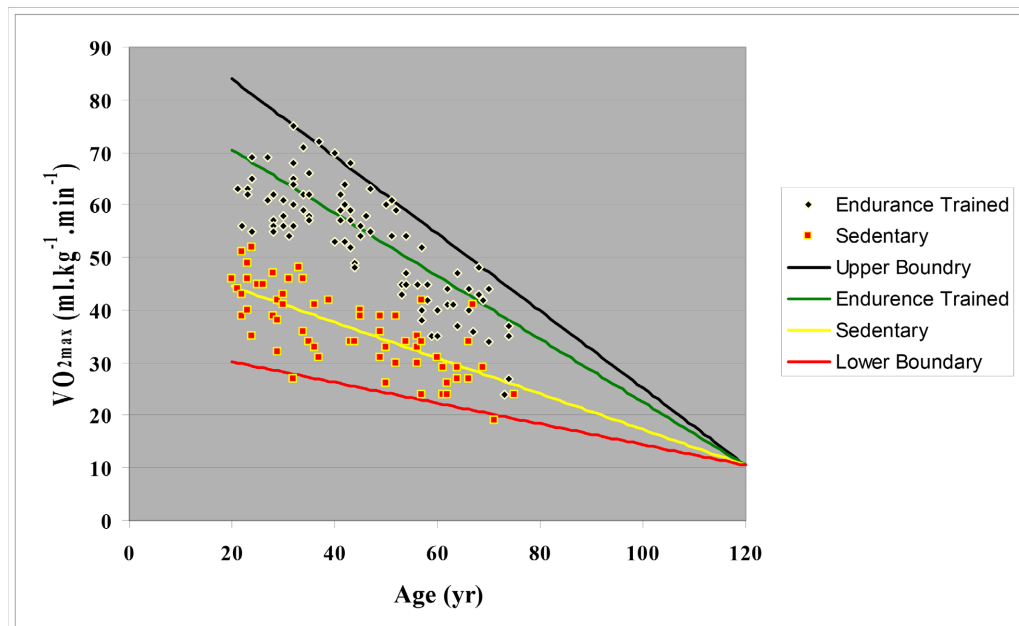


Figure 2. Reduction of VO_{2max} for men as a function of aging and fitness lifestyle. Data from Pimentel *et al.* [11].

- (0.45) estimate for control or average population (1/4 endurance training & 3/4 sedentary)
- (0.38) sedentary
- (0.22) approximate lower limit for sedentary
- (0.00) non-active bed rest

A = age (years)

G = gender coefficient (males: 10.5; females: 3.5) $ml \cdot kg^{-1} \cdot min^{-1}$

The only difference between male and female maximum oxygen uptake is the gender factor. The slope is the same for both males and females at the same relatively fitness. Predictions from Equation (1) matched the measured values for women with an $R^2 = 0.85$ and for men with an $R^2 = 0.75$. Both results were highly significant using the t distribution to predict the probability of type I error ($p < 0.001$). Equation (1) will be used later in the development.

2.2. Heart Health and Expected Life

A low value of maximum oxygen uptake (aerobic fitness) is associated with an increased risk of heart disease and early death as illustrated in **Figure 3** and **Figure 4**. The information in these two figures clearly illustrates the importance of aerobic fitness on heart health and longevity. Predictions in both of these figures are based on the cube of VO_{2max} . It will be shown later that WASO is also a function of the cube of VO_{2max} .

Predictions in **Figure 3** were made with the following equation:

$$R = 100 \sum_1^{N_y} \left(\frac{C_{hr}}{VO_{2max}} \right)^3 A_i^2 \quad (2)$$

where R = risk of fatal heart disease
 N_y = number of years from the beginning of the analysis
 C_{hr} = constant for heart risk for men
 A_i = age at year i
 i = year number

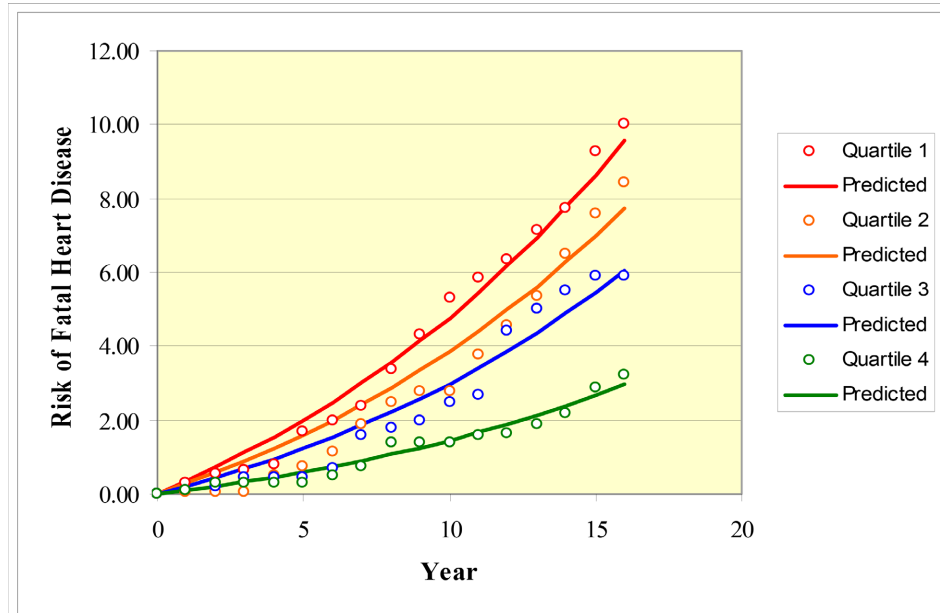


Figure 3. Measured and predicted risk of fatal heart disease as a function of age and maximum oxygen uptake. Data from Sandvik *et al.* [12].

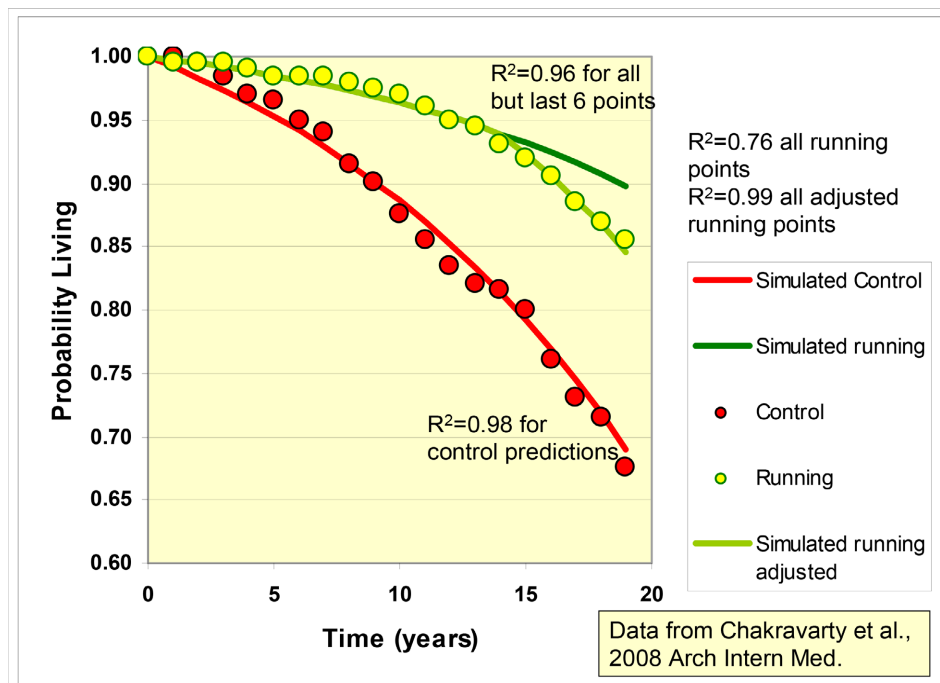


Figure 4. Probability of living as a function of age and maximum oxygen uptake. Data from Chakravarty *et al.* [13].

Sandvik *et al.* [12] reported a study involving 1960 Norwegian men. They divided the men in their study into four fitness quartiles. Their measured results reveal that fitness has a major effect on the risk of fatal heart disease. Aerobic fitness was not reported. The predicted VO_{2max} from Equation (1) was used with Equation (2) to estimate the risks of fatal heart disease as follows:

$$R = 100 \sum_1^{N_y} \left(\frac{C_{hr}}{107.4 RF \left(1 - \frac{A_i}{120} \right) + G} \right)^3 A_i^2 \tag{3}$$

A value of 0.34 for C_{hr} was determined by minimizing the least squares between predicted and measured risk values for the second quartile that was set as a sedentary fitness condition. This calibration was used in a similar analysis to determine the relative fitness for each of the other three quartiles. A comparison between predicted and measured risk values resulted in the R^2 values shown in **Table 1**. All results were highly significant ($p < 0.001$). The relative fitness values are provided in **Table 1**. The average of all four fitness quartiles was 0.42, which is in the high sedentary range for Equation (1). The top quartile of fitness has a 0.52 value, which is in the lower range of endurance training for Equation (1) as calibrated for both men and women in **Figure 1** and **Figure 2**. These fitness values are relative to the assumed average sedentary condition for fitness of quartile 2. While there is uncertainty about the exact relative fitness to use for each quartile, the cube relationship in Equation (1) along with the age variable describes the change in risk well over the 16-year time period in the study [12].

A similar cubic relationship was found to work well in predicting the probability of living. The probability of living or surviving is one minus the probability of death. The equation for the probability of surviving is expressed as follows:

$$P_s = 1 - \sum_1^{N_y} \left(\frac{0.427}{107.4 RF \left(1 - \frac{A_i}{120} \right) + G} \right)^3 A_i^2 \tag{4}$$

where P_s = probability of surviving

0.427 = calibration based on 21 years of data published in 2008 [13]

A value of 0.67 for endurance training was used to model the runners in the study by Chakravarty *et al.* [13]. The exact relative fitness is unknown. As a

Table 1. Relative fitness estimated from the data from Sandvik *et al.* [12].

Fitness Quartile	Relative Fitness	R ² Values	Description
4	0.52	0.95	Physically active
3	0.40	0.92	Sedentary (high)
2	0.38	0.93	Sedentary
1	0.36	0.98	Sedentary (low)

member of a running club; they are physically active and should be in the upper range of both **Figure 1** and **Figure 2**. A weighted average of $\frac{3}{4}$ sedentary and $\frac{1}{4}$ endurance-trained was used to model the control group. This weighted average is the same distribution of sedentary to endurance-trained (top quartile of fitness) as determined from the data of Sandvik *et al.* [12]. Results from this modeling with the measured data are shown in **Figure 4**. It was observed in **Figure 4** that a break in the trend of the running group appeared about 15 years into the study. It was assumed that this break occurred because most of the runners gave up their running commitment after they reached an age of 70 plus years. The control calibration for relative fitness of 0.45 was used instead of the 0.67 for endurance-trained after this breakpoint.

The control or average value for the control population in this analysis is 0.45 compared to the average value of 0.42 obtained by analyzing Sandvik *et al.* data [12]. These values differ by seven percent. Sandvik *et al.* [12] studied Norwegian Men—maybe a climate less conducive to physical exercise compared to the study by Chakravarty for people in California. Measured data from both studies are predicted well with a cube relationship of aerobic fitness.

The C_{hr} value of 0.34 is less than the 0.427 calibration in Equation (4). The risk for death from heart disease should be less than the risk for all causes of death.

The purpose of the analysis of the data in **Figure 3** and **Figure 4** was to illustrate that at least some of the risks affecting human health can be related to the inverse cube of maximum oxygen uptake. The use of linear regression to look for correlations for these relationships may reveal correlations but obviously a weak model as a prediction tool. Using only linear analysis and not having a well-defined measure of fitness in many studies may be the reason that sleep data is generally improved by exercise but has somewhat weak correlations. The hypothesis at this point is that WASO is an inverse cube function of aerobic fitness:

$$\text{WASO} = \left(\frac{C_{\text{WASO}}}{\text{VO}_{2\text{max}}} \right)^3 \text{TST} \quad (5)$$

where C_{WASO} = a constant ($15.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)

TST = total sleep time (min)

WASO = time awake after sleep onset (min)

Sleep literature was reviewed looking for measured values of WASO and $\text{VO}_{2\text{max}}$. To eliminate the effects of daily exercise, measurements of WASO from non-exercise or low-exercise days were used. WASO and $\text{VO}_{2\text{max}}$ data are provided in **Table 2**. To obtain a wide range of ages, a study by Hayashi *et al.* [14] with measured WASO was used with estimated values of $\text{VO}_{2\text{max}}$ using Equation (1) and relative fitness of 0.45—the same as the control population in **Figure 4**. These data were obtained from a mixture of cultures, genders, and ages.

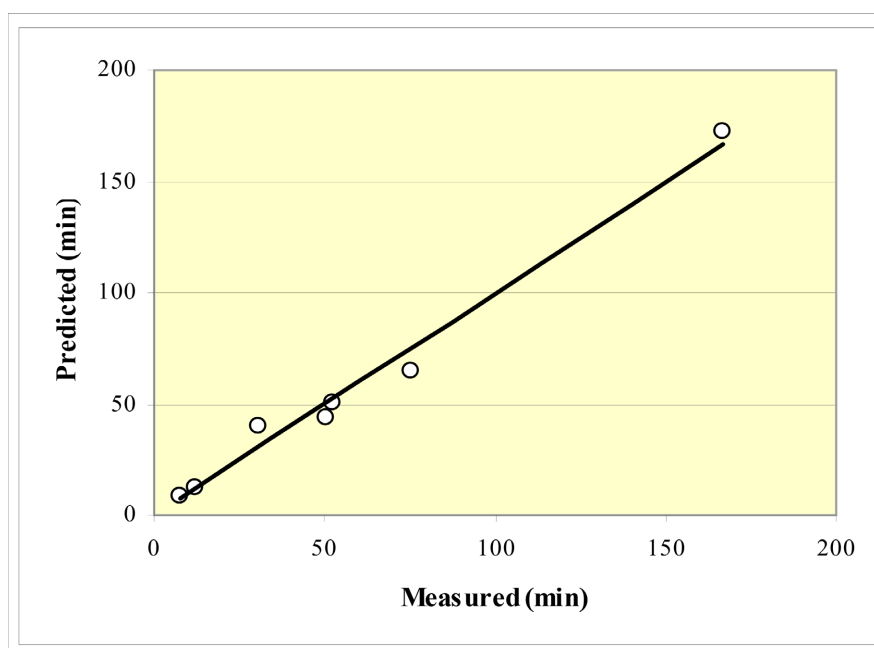
3. Results

Data from **Table 2** were used to test the relationship in Equation (5). A value of $15.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ was found for C_{WASO} . A comparison between measured and

Table 2. Reported measured WASO and predictions from Equation (5).

Source	VO _{2max} (ml·kg ⁻¹ ·min ⁻¹)	Measured WASO (min)	Predicted WASO (min)	Total Sleep (min)	Age (yrs)	Gender
Shapiro <i>et al.</i> 1981 [15]	55.8	7.5	9.0	435	20.7	100% M
Passos <i>et al.</i> 2011 [3]	26.0	75.2	64.5	317	48.0	78% FM
Passos <i>et al.</i> 2011 [3]	29.2	52.5	50.7	353	42.3	80% FM
Passos <i>et al.</i> 2011 [3]	30.7	50.5	43.5	352	48.0	78% FM
Passos <i>et al.</i> 2011 [3]	31.6	30.7	40.3	355	42.3	80% FM
Hayashi <i>et al.</i> 1982 [14]	21.1 ^a	167.0	172.0	451	82.1	67% FM
Hayashi <i>et al.</i> 1982 [14]	50.4 ^b	12.2	12.8	456	20.9	100% M

^aVO_{2max} estimated for mixed 5 male and 10 female (G = 5.83) and relative fitness = 0.45 (control population). ^bVO_{2max} estimated for young male (G = 10.5) and relative fitness = 0.45 (control population).

**Figure 5.** Comparison of measured and predicted WASO with Equation 5. Data from **Table 2.**

predicted WASO values is shown in **Figure 5**. From this comparison, an $R^2 = 0.98$ was obtained. This result is highly significant ($p < 0.001$).

The study by Passos *et al.* [3] provides clear evidence that maximum oxygen uptake is a variable that affects WASO. In their study, they selected people who reported difficulties with insomnia. WASO and VO_{2max} were measured both before and after an aerobic exercise program was started. After a period of time, VO_{2max} increased and WASO decreased. The range of change in this study was limited but seems to fit the same trend of other data in **Table 2** (**Figure 5**). Because of the excellent agreement between measured and predicted WASO with Equation (5), it can be concluded that VO_{2max} accounts for differences in age,

gender, and aerobic fitness.

While the inverse cube of VO_{2max} seems to model the variations in WASO well, this variable is usually unknown to most people. Equation (1) relates VO_{2max} to age, gender, and relative fitness. By using Equation (1) to estimate VO_{2max} in Equation (5), WASO can be estimated in terms of age, gender, and relative fitness:

$$WASO = \left(\frac{C_{WASO}}{107.4 RF \left(1 - \frac{A}{120} \right) + G} \right)^3 TST \quad (6)$$

Equation (6) was used with relative fitness of 0.26 (low relative fitness), 0.82 (upper relative fitness limit), and 0.45 (an average population relative fitness value) to predict values of WASO as a function of age (Figure 6). A gender factor of 7.0 (average of male and female) was used because the measured data were for a mix of male and female subjects.

Total sleep time as a function of age was obtained from Figure 2 by Ohayon *et al.* [7]. Measured WASO values as a function of age were obtained from Figure 1 of Ohayon *et al.* [7]. These values also are shown in Figure 6.

Predictions for average relative fitness (0.45) lie within the bulk of the reported measured values of WASO without specific calibration of relative fitness to match measured data. The lower boundary for WASO based on the upper limit of endurance training closely matches the lower boundary of the measured data. The upper boundary of the measured data seems to have the same shape as

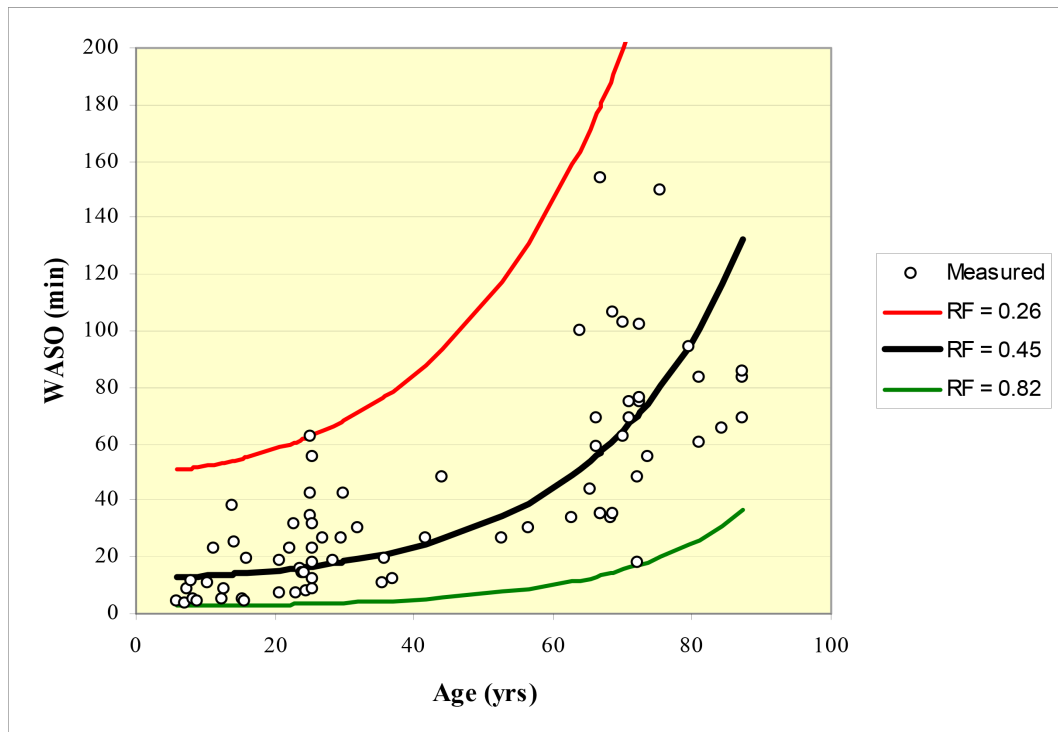


Figure 6. Illustration of effects of gender, age, and relative fitness on WASO. Measured data from Ohayon *et al.* [7].

the predicted value based on a relative fitness of 0.26, a low sedentary value. Based on Equation (6), some people with a lower limit of 0.22 for relative fitness would have a higher value of WASO than shown in **Figure 6**. People with such low values of relative fitness were probably eliminated from most if not all sleep studies because of other medical complications.

Based on predictions of WASO for females compared to males, women should have greater problems of insomnia than men associated with the aging process. This matches the report in reference [3] that women have 40 percent insomnia complaints compared to 35 percent of the general population.

Also, note that all of the measured WASO data reported by Ohayon *et al.* [7] are within the upper and lower boundaries for the predicted WASO using the relative fitness boundaries. The predictions for females have a wider range of WASO values than males for any age. The predicted WASO values for females are especially sensitive to the relative fitness input to Equation (6). Finally, note that WASO predictions are low for both males and females at high values of relative fitness. These simulated results imply that maximum oxygen uptake has a major effect on sleep efficiency.

With Equation (6), it is now possible to numerically relate WASO to relative fitness, age, and gender. The results from Equation (6) support the statement from Dolezal *et al.* [6] that exercise is usually beneficial for sleep. It supports their statement that exercise intervention has the most robust results for middle-aged and elderly adults. The differences in WASO associated with gender also seem to match observations reported in the literature for insomnia [3].

4. Discussion

Equations (2)-(6) all contain an inverse cube of VO_{2max} . Heart health and longevity are directly related to the inverse cube of aerobic fitness. Likewise, WASO is directly related to the inverse cube of aerobic fitness. This non-linear inverse cube relationship is one reason why linear correlations are not high between fitness and WASO.

The fact that some health risks, longevity, and WASO are all a function of the inverse cube of aerobic fitness may explain why long sleepers have an elevated risk of health issues and early death [16] [17]. Low maximum oxygen uptake certainly elevates risk factors for health and early death. Low aerobic fitness also increases WASO which increases time in bed to obtain needed sleep. When surveys are used to obtain sleep length, they typically measure time in bed instead of actual sleep time and may indirectly measure low aerobic fitness.

No attempt was made to look for differences in WASO associated with gender other than the variable G in Equation (1). Nevertheless, Equation 6 predicts higher values of WASO for women than for men of the same age and relative fitness. This gender effect seems to explain why insomnia reports are higher for women than men. This relationship of higher WASO for women than men has also been reported for men and women after experiencing trauma [18]. In **Fig-**

Figure 2 of Kobayashi and Mellman [18], the percentage of WASO for women is approximately double the value for men. This ratio is similar to the ratio for predictions of WASO for women and men for average relative fitness (0.45).

Based on Equation (6), three factors are major contributors to high values of WASO: age, gender, and relative fitness. Fortunately, relative fitness can be improved by aerobic exercise. By providing a prediction tool (Equation (6)), people can learn to better manage insomnia.

As discussed at the beginning of this paper, insomnia has two components: SOL and WASO. The focus of this paper was WASO. Nevertheless, it was observed in some of the measurements reported in the literature [2] [3] that high values of SOL are associated with high values of WASO. Sleep onset latency may, thus, in some cases be a function of maximum oxygen uptake.

In contrast, several studies on sleep found that elderly people have increased WASO but little or no increase in SOL compared to young adults [19] [20] [21] [22]. Carskadon and Dement [19], for example, reported for elderly volunteers a value of only 12 minutes for average MSLT (multiple sleep latency test). Sleep onset latency is the value of MSLT measured at bedtime. The volunteers had 126 minutes of WASO. Thus, the WASO was high as expected in association with age, but the MSLT was low. They [19] suggest that one reason MSLT and, thus, SOL might be low for the elderly, is respiratory disturbances that reduce sleep amount leading to some sleep debt. Certainly, people with sleep apnea tend to fall asleep quickly but have difficulty in obtaining a restful night of sleep. Low VO_{2max} associated with high WASO also tends to associate with reduced respiratory function.

Sleep onset latency data provided by Ohayon *et al.* [7] show little if any increase in SOL with age. Also, MSLT measured by Carskadon and Dement (1987) [19] revealed a cycle throughout a 24-hour period but little difference between young and old adults. Why some studies seem to suggest a connection between aerobic fitness and SOL and others do not is unknown. To complete a full analysis of age, gender, and aerobic fitness effects on insomnia, a study is needed to evaluate SOL as a function of aerobic fitness.

Finally, it is logical that high levels of WASO are associated with increased mortality risk as reported by Wallace *et al.* [5]. Risk of fatal heart disease (Figure 3), risk of death from all causes (Figure 4), and increase in WASO (Figure 5 and Figure 6) are all associated with the inverse cube of aerobic fitness. Aerobic fitness as measured by maximum oxygen uptake decreases as we age, which results in an increase of WASO with age.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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