Critical velocity and anaerobic distance capacity in prepubertal children.

Serge Berthoin, Georges Baquet, Gregory Dupont, Nicolas Blondel, Patrick Mucci

CRITICAL VELOCITY AND ANAEROBIC DISTANCE CAPACITY IN PRE-PUBERTAL CHILDREN

Serge Berthoin[1], Georges Baquet[1], Gregory Dupont[1], Nicolas Blondel[1-2], Patrick Mucci[2]

[1] Laboratoire d'Études de la Motricité Humaine, Faculté des Sciences du Sport et de l'Éducations Physique, Université de Lille 2, France

[2] Laboratoire d 'Analyse Multidisciplinaire des Pratiques Sportives, UFR STAPS de Liévin, Université de d'Artois, France

Corresponding author

Serge Berthoin

Laboratoire d'Etudes de la Motricité Humaine

Faculté des Sciences du Sport et de l'Education Physique

9, rue de l'Université

F-59790 Ronchin

France

tel : + 33 3 20 88 73 66

fax : + 33 3 20 88 73 63

e-mail : berthoin@hp-sc.univ-lille2.fr

ABSTRACT

This study was designed to calculate the critical velocity (v_{crit}) and the anaerobic distance capacity (ADC) of prepubescent children for running events. Thirty-four prepubertal children performed a graded field test until exhaustion in order to determine peak oxygen uptake (peakVO_2) and maximal aerobic velocity (MAV). Then, in a random order, they performed five runs until exhaustion (tlim) at relative velocities corresponding to 90, 95, 100, 105 and 110 % of MAV. The linear relationships between distance limit (dlim) and tlim were calculated in order to determine v_{crit} (slope of the relationship) and ADC (intercept). Very high individual coefficients of determination were found between dlim and tlim ($0.98<r^2<0.99$; $p<0.001$). The v_{crit} was significantly correlated to peakVO_2 ($r=0.73$; $p<0.001$). However, no relationship was found between ADC and the maximal accumulated oxygen deficit. In conclusion, our results indicated that, for children, the relationship between dlim and tlim could be calculated with tlim ranging from 2 to 10 min and that v_{crit} is a good indicator of the aerobic fitness of children. Nevertheless, further studies have to be conducted to validate the use of ADC as an indicator of children's anaerobic capacity.

Key Words: aerobic power – anaerobic capacity - comparison - model – performance

Résumé

Le but de cette étude était de calculer la vitesse (v_{crit}) et la capacité de distance anaérobie (CDA) d'enfants prépubères pour des exercices de course. Trente quatre enfants on effectué un test de terrain progressif et maximal afin de mesurer leur pic de consommation d'oxygène (picVO_2) et de déterminer leur vitesse maximale aérobie (VMA). Ils ont ensuite effectué, dans un ordre aléatoire, cinq courses continues jusqu'à épuisement (tlim) à des allures relatives représentantes 90, 95, 100, 105 et 110 % de VMA. Les relations linéaires entre les distances limites (dlim) et les tlim ont alors été calculées pour déterminer v_{crit} (pente de la relation) et CDA (ordonnée à l'origine). De très forts coefficients de détemination ont été calculés entre dlim et tlim ($0.98<r^2<0.99$; $p<0.001$). La v_{crit} était significativement corrélée au picVO_2 ($r=0.73$; $p<0.001$). Cependant, aucune relation n'a été trouvée entre la CDA et le déficit maximal accumulé en oxygène. En conclusion, nos résultats indiquent que la relation entre dlim et tlim peut être calculée à partir de tlim dont les durées sont comprises entre 2 et 10 min et que la v_{crit} est un bon indicateur de l'aptitude aérobie de enfants. Cependant, d'autres études sont nécessaires pour valider l'utilisation de la CDA comme indicateur de la capacité anaérobie des enfants.

Mots clés: puissance aérobie – capacité aérobie - comparaison - modélisation – performance

INTRODUCTION

Since the initial paper by Scherrer et al. (1954) many publications have been dedicated to the application of the critical power concept to general exercises (see Hill, 1993; Vandewalle et al., 1997 for review). Ettema (1966) is the first author to have applied this concept to running events. He proposed calculating the relationship between the distance limit (dlim) and time to exhaustion (tlim) as: dlim=(v_{crit}.tlim)+ADC where v_{crit} (critical velocity) and ADC (anaerobic distance capacity) were respectively the slope and intercept of this relationship (Figure 1: dlim=*f*(tlim). In adults research has demonstrated that the v_{crit} was not significantly different from the velocity corresponding to a 4 mmol.l^{-1} blood lactate concentration (Lechevalier et al., 1989) or the velocity at a maximal lactate steady state (Sid-Ali et al., 1991). The ADC parameter was assumed to represent the distance that could be covered with the energy equivalent of maximal oxygen deficit. It was found to be correlated to the maximal lactate concentration after exercise ([La]max) and maximal accumulated oxygen deficit (Hill et al., 1998).

Thus, the dlim=*f*(tlim) relationship, and its parameters, are assumed to provide an indication of performance over a wide range of times (or distances) and to provide an indication of both aerobic power (i.e. v_{crit}) and anaerobic capacity (i.e. ADC). In addition, v_{crit} could be considered as a velocity criterion to determine a running pace for training as are other physiological thresholds. This is of practical interest to coaches and physical educators, who cannot perform invasive measurements, yet require accessible methods to evaluate subjects' metabolic characteristics. For adults, many studies on the dlim=*f*(tlim) relationship have been conducted as reviewed by Hill (1993) and Vandewalle et al. (1997). In children who have specific cardiorespiratory and metabolic exercise responses, only three studies have been conducted on the dlim=*f*(tlim) relationship, but these were based on swimming exercise

(Denadai et al., 2000; Hill et al., 1995) or on cycling exercise (Fawkner and Armstrong, 2002). The results of these studies demonstrated that: the critical swimming velocity increased with age (Hill et al., 1995), and was significantly correlated to either swimming performance (Denadai et al., 2000; Hill et al., 1995) or to a swimming velocity corresponding to a 4 $mmol.l^{-1}$ blood lactate concentration (Hill et al., 1995). For cycling exercise, significant correlations were found between critical power and peak oxygen uptake ($peakVO_2$) and the ventilatory threshold (Fawkner and Armstrong, 2002). These findings are of particular interest as they support the use of the dlim=*f*(tlim) parameters to assess aerobic power in children. However, except for the study by Fawkner and Armstrong (2002), the assessment of v_{crit} and ADC were not validated with comparison to physiologically determined parameters, nor for running.

The aims of this study were to calculate the dlim=*f*(tlim) relationship in prepubertal children for running events and to assess the validity of the calculated parameters (v_{crit} and ADC) in comparison with physiologically determined parameters ($peakVO_2$ and maximal accumulated oxygen deficit).

MATERIALS AND METHODS

Subjects

Twenty-two girls (8-10 years) and twelve boys (9-11 years), attending a rural school, volunteered to enter the study. The children were not involved in any systematic training. Before the start of the experimentation, they were fully informed of the goals and the protocol of the study. Each child and his/her parents signed a consent form. This study received approval from the "Comité Consultatif de Protection des Personnes dans la Recherche Biomédicale de Lille"

Height and body mass were measured with a wall stadiometer (Vivioz medical) and a calibrated beam balance (Tanita TBF 543). Sexual maturity was evaluated from pubertal stages (Tanner, 1962): e.g., breast and pubic hair stages were assessed for girls and pubic hair and genital development stages for boys. Subjects were classified as prepubertal when the combined stage assessment was ≤ 3**.** The same physician made all the observations visually.

Protocol

Before entering the study, the children were familiarized with the testing modalities and the gas analyzer. Then, they performed six maximal field tests over a three-week period: one graded test and five continuous tests. The first test measured maximal aerobic velocity (MAV) and peak oxygen consumption (peakVO_2). Then the children performed five exercises until exhaustion, or time limit (tlim), in a random order, at velocities equal to 90%, 95%, 100%, 105%, 110% of MAV (tlim90 to tlim110). During the exercises, the velocities were monitored via a prerecorded soundtrack (graded test) or with a computer (continuous tests). All tests were performed in a covered place on a 150-m track marked with cones every 25 m. The soundtrack (or computer) emitted a brief sound that indicated to the children the moment when they had to pass near a cone to maintain a constant speed. During all tests, the children were verbally encouraged to run until exhaustion. To avoid any problem linked to a child's inability to maintain a constant speed, they ran with an adult. In all cases, the tests ended when the children were exhausted or when they could no longer maintain the required running velocity.

Cardiorespiratory parameters

During the graded and continuous tests, the heart rate (HR) was continuously monitored with a heart rate monitor (Accurex+, Polar Electro, Kempele, Finland). In both the graded test and the tlim110 test, respiratory parameters were measured breath by breath with a portable analyzer (Cosmed $K4b^2$, Rome, Italy), in order to determine the values for oxygen consumption (VO_2), carbon dioxide production (VCO_2), respiratory exchange ratio (RER) and ventilation (V_E). The measured values were averaged over 15-s periods. Before each test, the gas analyzers for O_2 and CO_2 were calibrated with a gas of known concentrations. The turbinflowmeter was calibrated with a 3-l syringe (Quinton Instruments, Seattle, USA).

Graded test

The Université de Montréal Track Test (Léger and Boucher, 1980) was used to determine peakVO_2 and MAV. Immediately after a 4-min warm-up at 7 $km.h^{-1}$, the test began at 8 $km.h^{-1}$. The velocity was then increased by 1 $km.h^{-1}$ every two minutes. The velocity at the last completed stage, increased by 0.5 $km.h^{-1}$ if the subject was able to run a half stage, was assumed to represent the MAV. PeakVO_2 was accepted as a maximal index, when, in addition to subjective indication of maximal effort, HR reached a value above 195 bpm or RER was >

1 (Tolfrey et al., 1998). All subjects satisfied these criteria. The highest level of VO_2 measured (15 s) during the test was assumed to represent the peakVO_2.

Continuous test

In a random order, five tlim were performed until exhaustion at velocities that represented 90 %, 95%, 100%, 105% and 110% of MAV. There was at least 24 h of recovery between two consecutive tests. The tlim were preceded by a standardized warm-up which consisted of a 4-min run at 7 $km.h^{-1}$ followed by a 2-min rest period. For each test, running time was measured to the nearest second. The maximal value for HR reached at each tlim was retained as peak heart rate (peakHR).

In the tlim110 trial, the ventilatory parameters were measured with the portable analyzer as described previously. Prior to the warm-up, subjects had to remain seated for 30 min. During the last 10 min of the rest period, ventilatory parameters were measured in order to determine resting VO_2 (VO_2r: i.e. the lowest value for VO_2 averaged over four consecutive 15-s periods).

Calculation of maximal accumulated oxygen deficit

The maximal accumulated oxygen deficit (MAOD) was calculated from the VO_2 values collected during the tlim110. This relative exercise velocity was assumed to allow children to reach exhaustion over a sufficient duration for MAOD to be calculated (Carlson and Naughton, 1998). The MAOD was calculated as the O_2 theoretically consumed to run at 110% of MAV minus the O_2 effectively consumed. The VO_2 theoretically needed to run at 110% of MAV was calculated from VO_2r and energy cost of running (Cr). The Cr was calculated from VO_2 values measured at 7 $km.h^{-1}$ or 116.6 $m.min^{-1}$ (VO_2-7) as: Cr = ($VO_2$7-VO_2r)/116.6. As the relationship between VO_2 and velocity is: VO_2=Cr.velocity+VO_2r, it is possible to estimate the VO_2 required to run at 110% of MAV by replacing the known velocity (MAV*1.1) in the equation. The O_2 required to run the tlim110 was calculated as the product of the theoretical VO_2 at 110% of MAV with time to exhaustion for the tlim110. The O_2 effectively consumed during this run was subtracted from this value to calculate MAOD. In addition to the MAOD, the distance that can be covered with this O_2 anaerobic equivalent was calculated as the quotient of MAOD and Cr.

Calculation of the dlim = f (tlim) relationship

The dlim=*f*(tlim) relationship was calculated from five tlim. If one measurement was not consistent with the others (i.e.: tlim90<tlim95<tlim100<tlim105<tlim110), the children had to perform an additional test. For example, if a tlim105 was shorter than a tlim110, the children had to perform an additional tlim105. If the tlim105 remained lower than the tlim110, the relationship was calculated with four experimental values (tlim105 was removed). To provide a more accessible estimation of this relationship all the combinations of two points were also used to calculate the dlim=*f*(tlim) relationship.

Statistics

Data were analyzed with StatView software (StatView+Graphic, Abacus Concepts). The experimental values were presented as mean±standard deviation. The mean cardiorespiratory values have been compared with a Student's t-test for paired (graded test versus tlim100) or unpaired series (boys versus girls). The times and HR values measured during the five continuous tests (tlim tests) have been compared with a two-way ANOVA (repeated measurements by gender). For both variables, there was no effect that could be attributed to a gender by time interaction, nor to a gender difference. Therefore, data for boys and girls were pooled and analyzed through a one-way ANOVA with repeated measurements. Where necessary, a post-hoc Scheffé test was used to compare experimental means. Linear regressions were calculated between the different parameters and for the determination of the dlim=*f*(tlim) relationships. To analyze the validity of the simplified methods for the dlim=*f*(tlim) determination, with only two tlim, the technique suggested by Bland and Altman (Bland and Altman, 1986) was applied. The difference in estimated parameters (v_{crit} or ADC) was plotted against means for v_{crit} or ADC. The mean difference (Bias) and the limits of agreement (Bias plus and minus two standard deviations) were graphically indicated. Bland and Altman (1986) suggested that if the values are within the average difference ±2 standard variations, and there is no correlation between the differences versus the averaged values, then the methods are equivalent. In all cases, the threshold for signification was set at $p<0.05$.

RESULTS

The means values for age, mass and height are presented in Table 1 for both girls and boys. All boys were at stage 1 for genital development and pubic hair. Nineteen girls were at stage 1 for breast and pubic hair, while for the remaining girls the combined stage assessment was ≤ 3. The children's mean MAV was 10.4±1.1 km.h^{-1} with significantly higher values ($p<0.001$) in boys (11.2 ± 1.1 km.h^{-1}) than in girls (9.9 ± 0.8 km.h^{-1}). The cardiorespiratory values for the graded test and tlim110 are presented in Table 2. For the entire population, the peakVO_2 ($p<0.05$) and peakHR ($p<0.001$) were significantly higher for the graded test, while the RER and V_E were significantly higher ($p<0.001$) for the tlim110. There was no significant difference between the maximal values for HR. Only for peakVO_2 (graded test and tlim100) and RER (tlim100), did boys demonstrate significantly higher values than girls ($p<0.05$). The results of tlim are presented in Table 3. The running time to exhaustion diminished significantly as the percentage of MAV increased ($p<0.001$) until the tlim110. However, the difference between tlim105 and tlim110 was not significant. The ANOVA for repeated measurements indicated no significant difference between the peakHR values measured during each tlim.

For twenty subjects, the dlim=*f*(tlim) relationship was calculated from five tlim, for twelve subjects it was calculated from four tlim, and for the remaining two subjects it was calculated from three tlim. For the whole group of subjects, linear adjustments were obtained ($0.98<r^2<0.99$, $p<0.001$). The average VO_2r was 6.4±1.0 ml.kg^{-1}.min^{-1} (range: 4.5-8.2 ml.kg^{-1}.min^{-1}), with no significant difference between boys and girls. The mean values for Cr, MAOD v_{crit} (km.h^{-1} and %MAV) and ADC are presented in Table 4. Except for v_{crit} when expressed in km.h^{-1} ($p<0.001$), no significant difference was observed between boys and girls for Cr, MAOD v_{crit} (%MAV) and ADC. The correlations between the values of MAOD and peakVO_2 (graded test) on the one hand, and the measured and calculated parameters from field tests on the other hand, are presented in Table 5. The v_{crit} was correlated to peakVO_2 (r = 0.73, p<0.001) and to MAV (r=0.91, p<0.001). The MAOD was moderately correlated to v_{crit} (r=0.41, p<0.05). No significant correlation was found between MAOD and ADC (p=0.08). When the product of MAOD and Cr was calculated, the resulting distance that could theoretically be covered (141.1±40.0m) was significantly correlated to ADC (r=0.43, p<0.05). However, these calculated distances significantly overestimated the ADC (p<0.05).

Multiple combinations of two tlim were performed in order to calculate the dlim=*f*(tlim) relationship. Only the subjects with five tlim measurements (n=20) were retained for this part of the study. The different calculated v_{crit} and ADC were compared to those calculated with five tlim which was assumed to be the gold standard. The most accurate calculations were obtained when the dlim=*f*(tlim) relationship was calculated from tlim110 and tlim90. When calculated from tlim110 and tlim90, the mean values for v_{crit} and ADC were 9.06±1.05 $km \cdot h^{-1}$ and 87.7±19.3 m, respectively. These values were not significantly different from those calculated with five tlim. Significant correlations were found between the parameters of the dlim=f(tlim) relationship when calculated with 5 tlim and 2 tlim (tlim110 and tlim90) for v_{crit} (r=0.99; p<0.001) and ADC (r=0.71; p<0.001). In addition, the technique proposed by Bland and Altman (1986) indicated graphically (Figures 2 and 3) that for v_{crit} and ADC, all values (minus one for v_{crit}) were between the limits of agreement. For v_{crit} (r=0.21, p=0.36) as for ADC (r=0.05, p=0.82) no relationship was found between the differences versus the averaged values.

DISCUSSION

The results of the present study indicate that, for running events, the dlim=v_{crit}.tlim+ADC relationship could be satisfactorily adjusted to the results of prepubertal children ($0.98<r^2<0.99$; $p<0.001$) for performances obtained from tlim at 90%, 95%, 100%, 105% and 110% of MAV. As is the case for adults, this model can be used to describe running performance of prepubertal children. The v_{crit} was significantly correlated to peakVO_2 ($r=0.73$; $p<0.001$), which suggests that this parameter is a good index of the aerobic fitness of a child. Conversely, the ADC was not correlated to the MAOD.

Characteristics of children

The peakVO_2 (45.2±6.7 $ml.kg^{-1}.min^{-1}$) was characteristic of moderately active children (Falgairette et al., 1991; Armstrong and Welsman, 2000). The HRmax (203±9 bpm) and RER (1.04±0.06) confirmed the maximal level of the graded test. The children's mean MAV (10.4 ±1.1 $km{\cdot}h^{-1}$ at 9.8±0.7 years) was similar to that reported by Berthoin et al. (1996) for 9 and 10 year old children, 9.4±0.8 $km{\cdot}h^{-1}$ and 10.6±1.2 $km{\cdot}h^{-1}$ respectively.

The children's tlim diminished significantly as the percentage of MAV increased. It is difficult to compare the tlim to those of others as, to our knowledge, only values for running tlim100 have been reported for children (Berthoin et al., 1996). The authors reported mean values of 213±112 s (9 years) and 252±99 s (10 years) for girls, while those of boys were 232±100 s (9 years) and 227±87 s (10 years). These reported values are similar to those found in the present study (244±79 s) for a mixed population of boys and girls with a mean age of 9.4 years. Conversely, all tlim were lower than those reported for adults (Blondel et al., 2001; Billat et al., 1995; Kachouri et al., 1996).

The lack of difference (p=0.08) between tlim110 and tlim105 could come from the hyperbolic nature of the tlim versus velocity relationship. Indeed, for intensities close to v_{crit}, small variations in velocity could induce large variations in tlim. However, for high velocities the tlim versus velocity has a tendency to become linear and small variations in velocity are associated with smaller variations in tlim than for exercises close to v_{crit}. This is particularly evident in children for whom the absolute range of velocities ($km.h^{-1}$) between two relative velocities (%MAV) is very short.

Our results indicated that at all relative velocities (%MAV) the tlim are lower in children than in adults and that the differences in tlim increase as the percentage of MAV decreases (Figure 4). This observation has practical implications for aerobic training in children as the duration of exercises, at selected percentages of MAV (or peakVO_2), should not follow the recommendations for adults. During intermittent exercises for example, the duration of the repetitions certainly have to be shortened in children when running at the same percentage of MAV as adults. Thus specific recommendations have to be established for children and further studies are needed to propose specific exercise sessions for training children.

Calculation of the dlim=f(tlim)relationship

In the present study, the dlim=f(tlim) relationship was calculated with 5 tlim for only twenty subjects. The number of tlim was chosen in order to accurately represent the relationship. However, for 12 subjects (35% of the population), we failed to measure 5 consistent values (tlim90<tlim95<tlim100<tlim105<tlim110). This could be explained by day-to-day variations of physiological parameters, or even motivation associated with little difference between the velocities at the different percentages of MAV (0.45 $km.h^{-1}$ for a child with a MAV of 9 $km.h^{-1}$, for example).

The high values of the coefficients of determination ($0.98<r^2<0.99$, $p<0.001$) together with the calculation of the dlim=*f*(tlim) underline the adequate nature of the linear model used to describe the relationship. The coefficients of determination are similar to those reported in children for swimming (Hill et al., 1995) or cycling (Fawkner and Armstrong, 2002). On the basis of the results, it could be concluded that exercises leading to exhaustion, reached in 2-3 to 10-12 min, could be retained to calculate the dlim=*f*(tlim) relationship in children. The relationship could also be calculated from competitive data (time trial data), which could give a slightly better representation than tlim data (Hill et al., 1995).

To provide less time-consuming methods for the determination of the dlim=*f*(tlim) relationship, all the combinations of calculations with only two tlim were performed. Only the subjects with five tlim (n=20) were included for this analysis. In each case, the v_{crit} and ADC parameters were compared to those obtained using five tlim, assumed to be the gold standard. It was when the dlim=*f*(tlim) relationship was calculated from tlim110 and tlim90 that the highest correlations between measurements of v_{crit} ($r=0.99$; $p<0.001$) and ADC ($r=0.71$; $p<0.001$) were obtained. In addition, the measurements were not significantly different and the technique by Bland and Altman (1986) indicated graphically significant agreement between the two methods (Figures 1 and 2). Furthermore, for both v_{crit} and ADC, no relationship was found between differences versus averaged values indicating that an additional simplification could also result in the measurement of the two tlim during the same day. Indeed, as demonstrated by Bishop and Jenkins (1995), two measurements of tlim performed the same day, with a sufficient rest period, could be proposed. Indeed, Fawkner and Armstrong (2002) have observed that the critical power of children measured from 3 tlim carried out on a same day with a 3-hour recovery period between each was not significantly different than the critical power calculated from tlim performed on different days. It could be of particular interest for children that recover more quickly than adults after intensive exercises (Hebestreit et al., 1993).

Parameters of the dlim=f(tlim)relationship

The mean values for v_{crit} and ADC cannot be compared to those reported in the literature as, to our knowledge, no study had focused on this topic for pre- or post-pubertal children. The absolute v_{crit} ($km \cdot h^{-1}$) was significantly lower than the values reported for adults (Blondel et al., 2001; Kachouri et al., 1996). Similar findings have been reported for swimming exercises by Hill et al. (1995) who demonstrated that absolute v_{crit} increased with age. A higher difference can easily be explained by a higher Cr in children than in adults (Daniels et al., 1978) despite similar peakVO_2 (Falgairette et al., 1991). However, when expressed as a percentage of MAV (85%) the results in children were of a similar level as those of adults for running events: 85%-90% (Blondel et al., 2001; Billat et al., 1995; Kachouri et al., 1996). This is an interesting result as v_{crit} has been presented as an index of aerobic endurance (time limit for running at velocities lower than the velocity associated with VO_2max) (Léger, 1996) that is not significantly different from the velocity corresponding to the 4 $mmol.l^{-1}$ blood lactate concentration (Lechevalier et al., 1989) or the velocity at maximal lactate steady state (Mocellin et al., 1991) in adults. However, despite v_{crit}, ventilatory anaerobic thresholds (Reybrouck et al., 1985) or onset of blood lactate accumulation (Sid-Ali et al., 1991) occurring at a similar or higher percentage of peakVO_2 (or MAV) than adults, children demonstrated lower tlim at all relative velocities (Figure 4). Thus, the interpretation of the different physiological thresholds (or v_{crit}) as an index of aerobic endurance has to be questioned as it implies that maximal time to exhaustion is longer in children than in adults.

The ADC of the children (94.4±30.4m) represented less than 50% of the values obtained in adults: 187±86 m (Kachouri et al., 1996) or 216±59 m (Billat et al., 1995). These results are in accordance with the lower values for ADC reported by Hill et al. (1995) in young swimmers and consistent with those obtained when comparing the anaerobic capacity of children and adults by means of MAOD measurement (Carlson et al., 1998) or Wingate tests (Armstrong et al., 2000).

The measurement of v_{crit} and ADC are of some help in explaining the lower tlim in children than in adults and also in explaining the increase of tlim100 with age (Berthoin et al., 1996). The linear relationship between dlim and tlim [dlim=(v_{crit}.tlim)+ADC] is mathematically equivalent to the hyperbolic relationship: tlim=ADC/(v-v_{crit}). This equation indicates that the tlim could be improved by increasing ADC or by decreasing the v-v_{crit} difference. As demonstrated in this study, the ADC parameter is considerably lower in children than in adults. However, the v-v_{crit} difference proved to be lower in children. In children with MAV of 10 $km \cdot h^{-1}$ and a v_{crit} of 85% of MAV for example, the v-v_{crit} difference is 1.5 $km \cdot h^{-1}$, while for adults with a MAV of 15 $km \cdot h^{-1}$ and a similar relative v_{crit} (85% of MAV), the v-v_{crit} difference will be equal to 2.2 $km \cdot h^{-1}$. During growth, the combined evolution of ADC and v-v_{crit} difference are among the parameters that could partly explain an increase in tlim.

Physiological significance of the v_{crit} and ADC parameters

Our results indicated that v_{crit} was significantly correlated to peakVO_2 ($r=0.73$, $p<0.001$) and to MAV ($r=0.91$; $p<0.001$), an index of aerobic performance. This result is in line with those of Fawkner and Armstrong (2002) who reported significant correlations between critical power and peakVO_2 ($0.91<r<0.95$, $p<0.001$) and ventilatory threshold ($0.75<r<0.77$; $p<0.001$). Others have also found significant correlations between swimming v_{crit} and performances over 400 m (Wakayoshi et al., 1992) and 457 m or 1509 m (Hill et al., 1995). These different results indicated that the v_{crit} is a good index of the aerobic power and the aerobic performance of children. No relationship was found between ADC and MAOD ($p=0.08$). The mean calculated MAOD (34.1 ± 12.3 $ml.kg^{-1}$) was close to that reported for children of the same age by Carlson and Naughton (1998). However, a large variability of MAOD was observed, as demonstrated by a high coefficient of variation. In the present study, a simplified method of MAOD determination was performed using resting VO_2 and Cr. More submaximal VO_2 are certainly needed to calculate the VO_2 versus velocity relationship and to obtain a more accurate determination of the MAOD. In adults, the ADC parameter was found to be a reflection of anaerobic fitness determined from cycle ergometry (Jenkins and Quigley, 1991). However, for running events, the ADC has not been related to indicators of anaerobic capacity (Housh et al., 1992). Determining the distance that can be covered using the MAOD provided an alternative determination of the anaerobic capacity of the children. This distance was significantly correlated to ADC ($r=0.43$, $p<0.05$) but was also significantly higher. However, Hill et al. (1995) showed that, for children, correlations between ADC and peak lactate concentration were only observed for the children for whom the most accurate adjustment of the dlim=*f*(tlim) relationship was obtained. In general, the results reported in the literature indicated that the determination of the ADC parameter was more protocol-dependent and that ADC values presented a lower correlation to other indicators of anaerobic capacity than v_{crit} do with indicators of aerobic power (Hill, 1993; Vandewalle et al., 1997). Nevertheless, the validity of ADC measurement to evaluate children's anaerobic capacity requires further investigation.

Conclusions

In children, the dlim versus tlim relationship can be calculated with running times to exhaustion ranging between 2 and 10 min. The v_{crit} seems to be an interesting predictor of the aerobic power of children. Conversely, the use of ADC as a predictor of anaerobic capacity requires further investigation. From a practical point of view, the relationship can be accurately calculated from only tlim90 and tlim110 or even with performances over 2 min or 10 min. By knowing the dlim=*f*(tlim) relationship, the performance of children can be predicted over a large range of times (or distances). However, further studies are needed to test the sensitivity of v_{crit} and ADC to training or its evolutions with growth and maturation. In addition, studies are needed to test the accuracy of prescribing exercise intensities for training with the v_{crit} as a velocity criterion.

REFERENCES

Armstrong, N., Welsman, J.R., Williams, C.A., and Kirby, B.J. (2000). Longitudinal changes in young people's short-term power output. **Med. Sci. Sports Exerc**. 32: 1140-1145.

Armstrong, N. Welsman, J.R. (2000). Development of aerobic fitness during childhood and adolescence. Ped. Exerc. Sci. 12: 128-149

Berthoin, S., Baquet, G., Mantéca, F., Lensel-Corbeil, G., and Gerbeaux, M. (1996). Maximal aerobic speed and running time to exhaustion for children 6 to 17 years old. **Ped. Exerc. Sci**. 8: 234-244.

Billat, V., Renoux, J.C., Pinoteau, J., Petit, B., and Koralsztein, J.P. (1995). Times to exhaustion at 90, 100 and 105 % of velocity at VO_2max (maximal aerobic speed) and critical speed in elite long distance runners. **Arch. Physiol. Biochem**. 103: 129-135.

Bishop, D., and Jenkins, D.G. (1995). The influence of recovery duration between periods of exercise on the critical power function. **Eur. J. Appl. Physiol**. 72: 115-120.

Bland, J.M., and Altman, D.G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. **Lancet** 1: 307-310.

Blondel, N., Berthoin, S., Billat, V., and Lensel, G. (2001). Relationship between run times to exhaustion at 90, 100, 120, 140% of vVO_2max and velocity expressed relatively to critical velocity and maximal velocity. Int. J. Sports Med. 22: 27-33

Carlson, J., and Naughton, G.A. (1998). Assessing oxygen deficit in children. In: E. VanPraagh (Ed.), **Pediatric Anaerobic Performance**, pp. 119-136. Human Kinetics: Champaign, Il.

Daniels, J.T., Oldridge, N., Nagle, F., and With, N. (1978). Differences and changes in VO_2 among young runners 10-18 years of age. **Med. Sci. Sports** 10: 200-203.

Denadai, B.S., Greco, C.C., and Teixeira, M. (2000). Blood lactate response and critical speed in swimmers aged 10-12 years of different standards. **J. Sports Sci**. 18: 779-784.

Ettema, J.H. (1966). Limits of human performance and energy production. **Int. J. Angew. Physiol.** 22: 45-54.

Falgairette, G., Bedu, M., Fellmann, N., Van-Praagh, E., and Coudert, J. (1991). Bio-energetic profile in 144 boys aged from 6 to 15 years with special reference to sexual maturation. **Eur. J. Appl. Physiol**. 62: 151-156.

Fawkner, S.G., Armstrong, N. (2002). Assessment of critical velocity with children. Ped. Exerc. Sci. 14: 258-268

Hebestreit, H., Mimura, K., and Bar-Or, O. (1993). Recovery of muscle power after high-intensity short-term exercise: comparing boys and men**. J. Appl. Physiol**. 74: 2875-2880.

Hill, D.W. (1993). The critical power concept: A review. **Sports Med**. 16: 237-354.

Hill, D.W., Ferguson, C.S., and Ehler, K.L. (1998). An alternative method to determine maximal accumulated O_2 deficit in runners. **Eur. J. Appl. Physiol**. 79: 114-117.

Hill., D.W., Steward, R.P., and Lane, C.J. (1995). Application of the critical power concept to young swimmers. **Ped. Exerc. Sci**. 7: 281-293.

Housh, T.J., Johnson, G.O., McDowell, S.L., Housh, D.J., and Pepper, M.L. (1992). The relationship between anaerobic running capacity and peak plasma lactate. **J. Sports Med. Phys. Fitness**. 32:117-122.

Jenkins, D.G., and Quigley, B.M. (1991). The y-intercept of the critical power function as a measure of anaerobic work capacity. **Ergonomics** 34: 13-22.

Kachouri, M., Vandewalle, H., Billat, V., Huet, M., Thomaïdis, M., Jousselin, E., and Monod, H. (1996). Critical velocity of continuous and intermittent running exercise. An example of the limits of the critical power concept. **Eur. J. Appl. Physiol**. 73: 484-487.

Lechevalier, J.M., Vandewalle, H., Chatard, J.C., Gandrieu, A., Besson, F., and Monod, H. (1989). Relationship between the 4 mmol running velocity, the time-distance relationship and the Léger-Boucher test. **Arch. Int. Physiol. Bioch. Biophys**. 97: 355-360.

Leger, L. (1996). Aerobic performance. In:. D. Docherty (Ed.), **Measurement in pediatric exercise science**, pp. 183-223. Human Kinetics : Champaign, Il.

Leger, L., and Boucher, R. (1980). An indirect continuous running multistage field test: the Université de Montréal Track Test. **Can. J. Appl. Spt. Sci**. 5: 77-84.

Mocellin, R., Heusgen, M., and Gildein, H.P. (1991). Anaerobic threshold and maximal steady-state blood lactate in prepubertal boys. **Eur. J. Appl. Physiol**. 62: 56-60.

Reybrouck, T., Weymans, M., Stijns, H., Knops, J., and x VanderHauwaert, J. (1985). Ventilatory anaerobic threshold in healthy children. **Eur. J. Appl. Physiol**. 54: 278-284.

Scherrer, J., Samson, M., and Paleologue, A. (1954). Etude du travail musculaire et de la fatigue, Données ergométriques obtenues chez l'homme. **J. Physiol. (Paris)** 46: 887-916.

Sid-Ali, B., Vandewalle, H., Chaïr, K., Moreaux, A., and Monod, H. (1991). Lactate steady state velocity and distance-exhaustion time relationship in running. **Arch. Int. Physiol. Bioch. Biophys**. 99: 297-301.

Tanner, J. M. (1962). Growth at Adolescence (2nd ed.). Boston: Blackwell.

Tolfrey, K., Campbell, I.G., Batterham, A.M. (1998). Aerobic trainability of prepubertal boys and girls. **Ped. Exerc. Sci.** 10: 248 - 263

Vandewalle, H., Vautier, J.F., Kachouri, M., Lechevallier, J.M., and Monod, H. (1997). Work-exhaustion time relationships and the critical power concept: A critical Review. **J. Sports Med. Phys. Fitness** 37: 89-102.

Wakayoshi, K., Yoshida, M., Udo, T., Kasai, T., Moritani, Y., Mutoh, Y., and Miyashita, M. (1992). A simple method for determining critical speed as swimming fatigue threshold in competitive swimming. **Int. J. Sports Med**. 13: 367-371, 1992.

Acknowledgment: The authors wish to express special thanks to the children for their enthusiasm and participation, the teachers from the Illies primary school for their welcome and availability, and the "Inspection Pédagogique du Nord", particularly Mr Fromont for allowing the experiments.

Table 1 Age and anthropometric characteristics of children.

	Girls (n=22)	Boys (n=12)
Age (years)	9.5±0.7	9.5±0.8
Mass (kg)	36.3 ±8.4	34.4±7.2
Height (m)	1.39±0.08	1.39±0.05

Table 2 Cardiorespiratory parameters measured during the graded and tlim110 tests.

	Graded test	Tlim110
Boys and girls		
peakVO_2 ($ml.kg^{-1}.min^{-1}$)	45.2 ± 6.7	43.3 ± 5.3***
$V_E$max ($l.min^{-1}$)	59.5 ± 10.6	63.4 ± 10.2***
RER	1.04 ± 0.06	1.21 ± 0.09***
HRmax (bpm)	203 ± 9	200 ± 10
Girls		
peakVO_2 ($ml.kg^{-1}.min^{-1}$)	43.3 ± 5.3	42.1 ± 5.3*
$V_E$max ($l.min^{-1}$)	58.2 ± 11.9	63.0 ± 10.6***
RER	1.04 ± 0.07	1.18 ± 0.08***
HRmax (bpm)	204 ± 9	202 ± 11
Boys		
peakVO_2 ($ml.kg^{-1}.min^{-1}$)	48.7 ± 8.1	45.9 ± 4.7***
$V_E$max ($l.min^{-1}$)	61.9 ± 8.1	65.2 ± 9.8
RER	1.04 ± 0.05	1.26 ± 0.11***
HRmax (bpm)	201 ± 7	198 ± 7

Tlim110: time to exhaustion at 110% of maximal aerobic velocity; peakVO_2: peak oxygen uptake; $V_E$max: maximal ventilation; RER: respiratory exchange ratio; HRmax: maximal heart rate.

*: significantly different from graded test for the same group ($p < 0.05$)

***: significantly different from graded test for the same group ($p < 0.001$)

Table 3 Exercise times to exhaustion and peakHR values for tlim at 90%, 95%, 100%, 105% and 110% of MAV.

	Tlim90	Tlim95	Tlim100	Tlim105	Tlim110
time (s)	667 ± 311	380 ± 177***	244 ± 79***	151 ± 47***	129 ± 34
peakHR (bpm)	201 ± 9	201 ± 8	200 ± 7	200 ± 7	199 ± 7

Tlim90, Tlim95, Tlim100, Tlim105, Tlim110: times to exhaustion at 90, 95, 100, 105 and 110% of maximal aerobic velocity, respectively; peakHR: peak heart rate.

***: significantly different from previous column ($p < 0.001$)

Table 4 Mean calculated parameters.

	Girls	Boys	Boys and girls
Cr ($ml.kg^{-1}.m^{-1}$)	0.240 ± 0.032	0.235 ± 0.019	0.238 ± 0.028
MAOD ($ml.kg^{-1}$)	34.3 ± 11.8	33.6 ± 13.6	34.1 ± 12.3
ADC (m)	95.3 ± 32.1	92.8 ± 28.4	94.4 ± 30.4
V_{crit} ($km.h^{-1}$)	8.4 ± 1.0***	9.7 ± 0.9	8.8 ± 1.1
V_{crit} (%MAV)	84.2 ± 5.8	86.4 ± 1.7	85.0 ± 4.9

Cr: energy cost of running; MAOD: maximal accumulated oxygen deficit ; ADC: anaerobic distance capacity; V_{crit}: critical velocity

***: significantly different from boys ($p < 0.001$)

Table 5 Correlations between physiological parameters and calculated or measured parameters from field tests.

	v_{crit} (km·h^{-1})	v_{crit} (%MAV)	ADC (m)
peakVO_2 (ml.kg^{-1}.min^{-1})	0.77 ***	0.44 **	0.02
MAOD (ml.kg^{-1})	0.41 *	0.22	0.30
MAV (km·h^{-1})	0.91 ***	0.20	0.06

V_{crit}: critical velocity; ADC: anaerobic distance capacity; peakVO_2: peak oxygen uptake measured during the graded test; MAOD: maximal accumulated oxygen deficit; MAV: maximal aerobic velocity.

*: significantly correlated ($p < 0.05$)

**: significantly correlated ($p < 0.01$)

***: significantly correlated ($p < 0.001$)

Figure captions

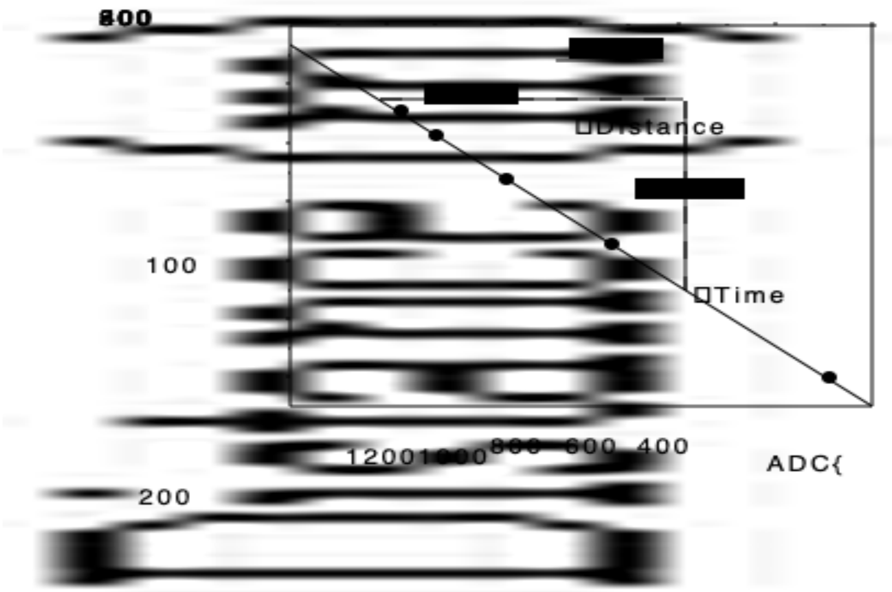
Figure 1. An example of the dlim versus tlim relationship.

Figure 2. Average between critical velocities calculated with 5 tlim and with 2 tlim (tlim110 and tlim90) plotted against the differences between the two critical velocities.

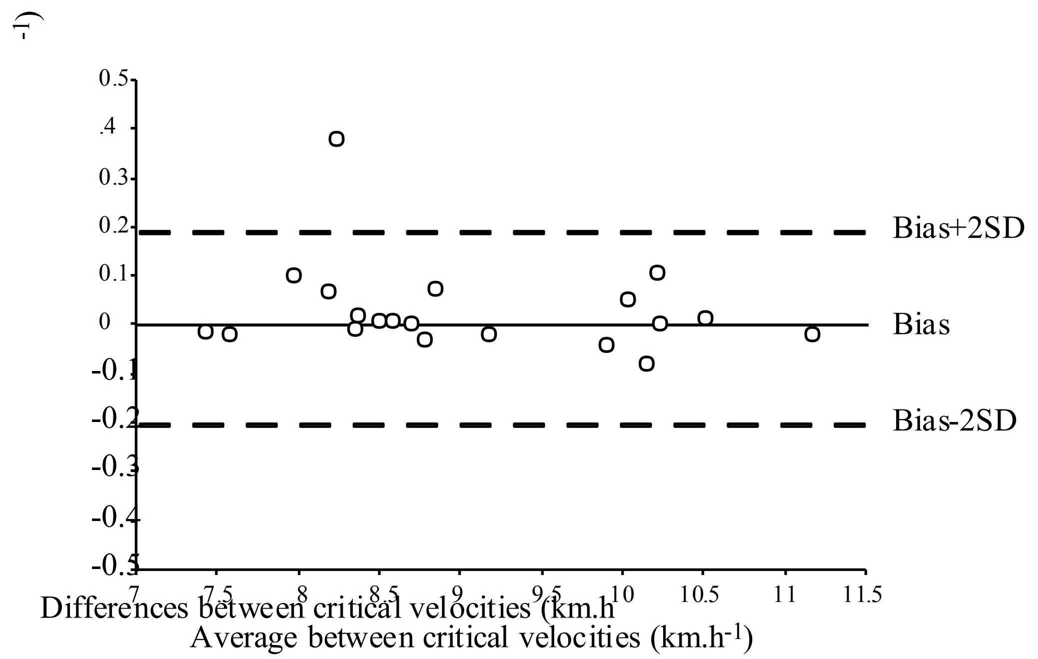
Figure 3. Average between anaerobic distance capacities calculated with 5 tlim and with 2 tlim (tlim110 and tlim90) plotted against the differences between the two anaerobic distance capacities

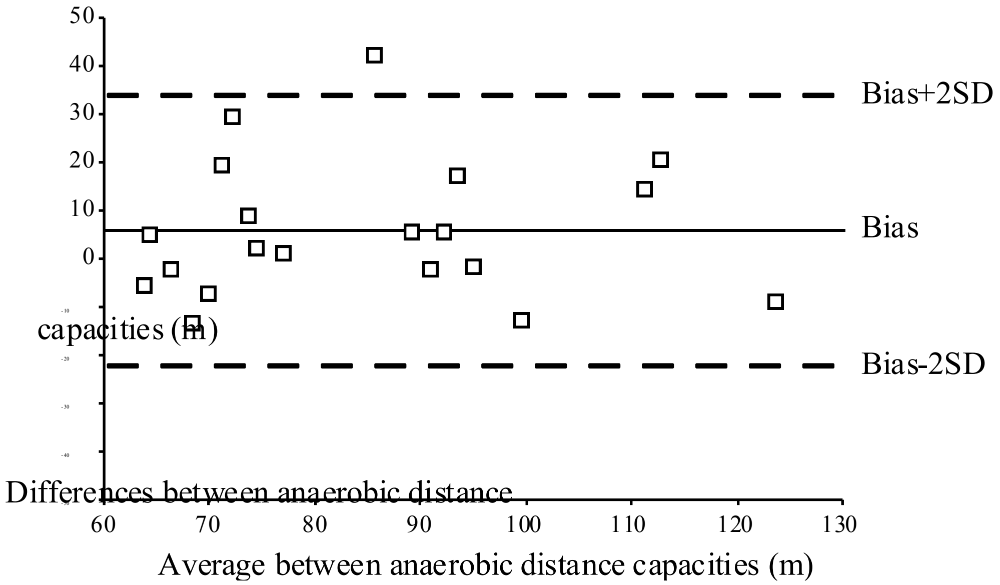
Figure 4. Relationships between tlim and % percentage of MAV for the children in the present study and those of non-specifically aerobic-trained adults (Blondel et al., 2001; Kachouri et al., 1996) and aerobic-trained adults (Billat et al., 1995).

Figure 5. The dlim versus tlim relationship for mean values.

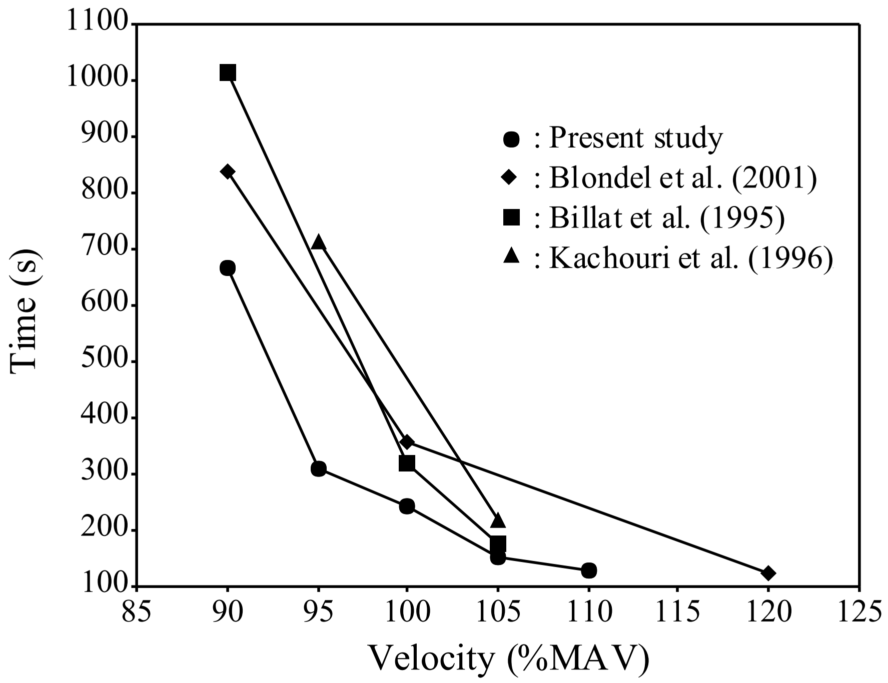


□Time □Distance = Critical velocity

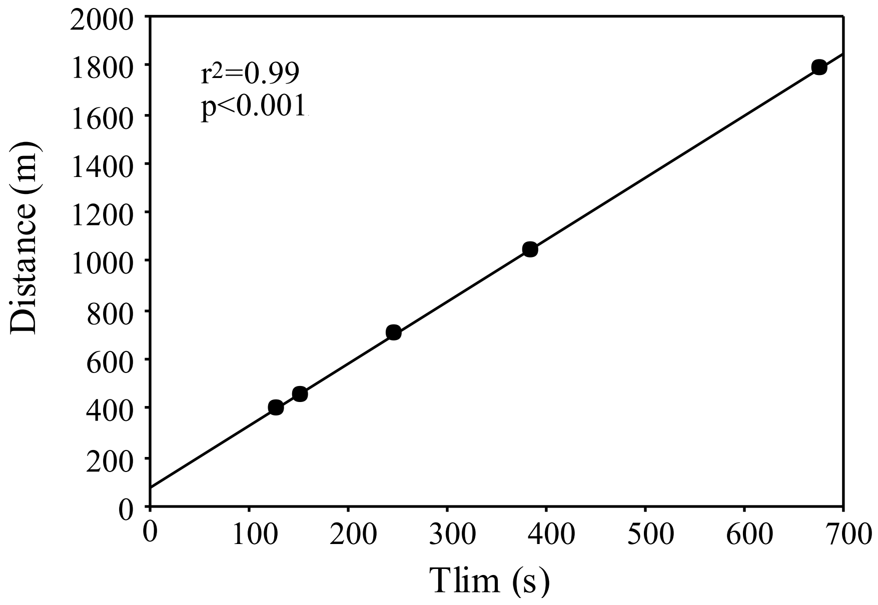

-1)
0.5
.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Bias+2SD
Bias
Bias-2SD
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
Differences between critical velocities (km.h
Average between critical velocities (km.h-1)



Bias+2SD
Bias
Bias-2SD
Differences between anaerobic distance capacities (m)
Average between anaerobic distance capacities (m)
50
40
30
20
10
0
60
70
80
90
100
110
120
130



Time (s)
1100
1000
900
800
700
600
500
400
300
200
100
85
90
95
100
105
110
115
120
125
Velocity (%MAV)
: Present study
: Blondel et al. (2001)
: Billat et al. (1995)
: Kachouri et al. (1996)


r2=0.99
p<0.001
Distance (m)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
100
200
300
400
500
600
700
Tlim (s)