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Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers

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ABSTRACT

Purpose: To compare the dynamics of $\dot{V}O_2$, blood lactate ($[La]_b$), total energy expenditure (E_{tot}), and contributions of the aerobic (E_{aer}), alactic anaerobic ($E_{an,al}$) and lactic anaerobic ($E_{an,lac}$) metabolic energy pathways over four consecutive 25-m laps (L_{0-25}, L_{25-50}, L_{50-75}, L_{75-100}) of a 100-m maximal freestyle swim. **Methods:** Elite swimmers comprising 26 juniors (16 ± 1 y) and 23 seniors (24 ± 5 y) performed 100 m at maximal speed, and then three trials (25, 50 and 75 m) at the same pace as that of the 100 m. $[La]_b$ was collected and $\dot{V}O_2$ was measured 20 s post-exercise using a Cosmed K4 b2 analyser. **Results:** The estimated energetic contributions (%E_{tot}) for the 100-m trial were E_{aer}: 51 ± 8%, $E_{an,al}$: 18 ± 2% and $E_{an,lac}$: 31 ± 9% (mean ± SD). $\dot{V}O_2$ increased from L_{0-25} to L_{25-50}: 3.5 (3.4-3.7) to 4.2 (4.0-4.3) $l{\cdot}min^{-1}$ [mean (90% CI)] and then stabilized: 4.1 (3.9-4.3), 4.2 (4.0-4.4) in the 2nd 50-m. E_{tot} (138 ±18, 168 ± 26 kJ; juniors, seniors), $E_{an,al}$ (27 ± 3, 30 ± 3 kJ), and $E_{an,lac}$ (38 ± 12, 62 ± 24 kJ) were 11-58% higher in seniors. Faster swimmers (n=26) had higher $\dot{V}O_2$: 4.6 (4.4-4.8) vs. 3.9 (3.6-4.2 $l{\cdot}min^{-1}$) and E_{aer} power was associated with fast performances ($p<0.001$). **Conclusion:** Faster swimmers were characterized by higher $\dot{V}O_2$ and less time to reach the highest $\dot{V}O_2$ at ~50 m of the 100-m swim. Anaerobic qualities become more important with age.

INTRODUCTION

The evaluation of metabolic capacities and their relative contributions to performance in different events informs the training programs for competitive pool swimming, from short (50 m) to long (1500 m) distances.[1-2] This evaluation is need for coaches and sports scientists to more effectively prescribe and monitor the training of elite swimmers. Moreover, in several swimming federations, the distributions of intensity zones over the course of a swimming career are theoretically based on the changes in metabolic and physiological capacities over the course of maturation.

For studies of 100m trials, swimming speeds have been markedly different (1.5-1.9 $m.s^{-1}$), as have the reported metabolic profiles. For example, results for the aerobic-anaerobic contributions (expressed as % of total energy expenditure, $\%E_{tot}$) have ranged between ~33-67%,[2] ~31-69%[3] and ~43-57%.[4] Another study combining field measurements with modelling of muscle energy metabolism using computer simulation estimated the energy distribution as ~41-59%.[5] These discrepancies could relate to different testing methods (e.g. direct exercise measurements vs. backward extrapolation, pool vs. flume swimming, dive vs. wall starts). For the protocols in which gas exchanges were continuously measured,[2,3] a constant swimming speed was imposed, as opposed to real competitive conditions. Differences in speed patterns and swimming techniques could modify the metabolic and physiological responses and undermine the usefulness of assessments in high-level swimmers."[6]

Divergent findings are also likely related to the wide dispersion of ages and performance levels in the swimmer cohorts. It is well known that growth and maturation affects cardiovascular responses[7,8] and skeletal muscle energetics.[9] During puberty, maximal oxygen uptake ($\dot{V}O_{2max}$) related to body mass increases modestly,[7,10] with larger changes in muscle power and anaerobic capacity.[11] At the muscular level, these pubertal changes are associated with a decrease in the aerobic contribution to ATP production, an increase in the rate of PCr breakdown, and higher reliance on glycolytic motor units.[9,11] In shorter events (1-2 min), the best performers typically exhibit high oxidative potential (high $\dot{V}O_{2\,max}$ and fast O_2 kinetics)[12] and high anaerobic power.[7,13]

No swimming study to date has compared the metabolic contributions during a 100-m trial at a real race pace as a function of age and expertise level. The aim of this study was therefore to measure the relative metabolic energy contributions in elite junior and senior swimmers performing a 100-m trial using all the formal race elements (dive start, glide phases, tumble turns). We expected metabolic profiles would vary substantially with age and performance level, with higher alactic and lactic but lower aerobic energy contribution in older and faster swimmers.

METHODS

Participants

Forty-nine elite competitive male swimmers volunteered for this study. The group comprised 26 juniors [16 ± 1 years, 65 ± 9 kg, 178 ± 8 cm, 510 ± 124 Fédération Internationale de Natation (FINA) points; mean ± SD] and 23 seniors including 4 World championships medallists (24 ± 5 years, 78 ± 5 kg, 188 ± 7 cm, 640 ± 77 FINA points). The 8 butterfly, 8 backstroke, 8 breaststroke and 25 freestyle swimmers undertook 6 to 11 training sessions per week. This study received approval from the Ethics Committee for Clinical Sport Research of the INSEP, France.

Experimental protocol

The experimental sessions took place over 4 consecutive days in a 50-m pool. Each swimmer performed a maximal effort 100-m time trial in his best event after a pre-race warm-up. The performance times were [mean (90% CI)]: butterfly: 61-s (59-63), backstroke: 60-s (58-62), breaststroke: 71-s (66-77) and freestyle: 56-s (55-58). On the following days, each swimmer performed separate 75-, 50- or 25-m trials at the same pace of the initial 100-m time trial on the first day. The swimmers were paced with three complementary methods: each swimmer was fitted with an audible digital metronome (Aqua Pacer Swimming) that signalled the pace every 12.5 m. A study investigator also signalled the pace by tapping on a metal pole in the pool. Another investigator walked alongside the pool edge keeping the pace from one marker to the next. The swimmers were filmed to assess their times (s) and stroke rates in each 25-m length. To compare performances with the four stroke styles, all performance times were converted to FINA points (http://www.fina.org/content/fina-points). The four strokes were coded from 1 to 4 from the lowest to the highest expected energy cost (freestyle, backstroke, butterfly and breaststroke) according to established criteria.[2]

Metabolic measures

Expired gases and $\dot{V}O_2$ were measured immediately after each trial using a portable gas analysis system (K4 b2, Cosmed, Italy) connected to an oronasal mask. The mask was applied to the swimmer's face for 1 min as soon as he stopped swimming and raised his head out of the water. The $\dot{V}O_2$ (ml·min^{-1} and ml·min^{-1}·kg^{-1}) attained at the end of each pool length was estimated from a single post-exercise average (20-s mean of breath-by-breath collection).[14] Capillary blood (5 μl) was collected from a fingertip and blood lactate concentration ($[La]_b$, mmol.l^{-1}) was measured before and then 2, 4, 6 and 8 min after each trial (only the highest value was retained) using a Lactate Pro analyser (Arkray, Japan). Lactatemia measurements were doubled to avoid measurement errors. When the first two measurements did not agree, a third measurement was made and the average of the two closest measures was taken. Net $[La]_b$ ($[La]_{b,net}$) was computed as the difference between the post-exercise and rest $[La]_b$.

Metabolic energy calculations

Total amount of metabolic energy expenditure (E_{tot}, kJ) during each of the 100-m supramaximal swims was calculated as the sum of three terms:[2,15,16,17]

$$E_{tot} = E_{an,al} + E_{an,lac} + E_{aer} \quad (1)$$

where E_{tot} (kJ) is the total amount of metabolic energy; $E_{an,alac}$ and $E_{an,lac}$ (kJ) are the metabolic energy derived from anaerobic alactic (phosphagens) and lactic (glycolysis) metabolic sources, respectively, and E_{aer} is the amount of aerobic (oxidative) energy.

Anaerobic alactic energy contribution ($E_{an,al}$, kJ) was estimated from complete utilization of PCr stores in the active muscles:[15]

$$E_{an,al} = [PCr]_m (1 - e^{-t/\tau}) \cdot M_b \quad (2)$$

where $[PCr]_m$ (mmol·kg^{-1} wet muscle) is the phosphocreatine concentration at rest, assuming that PCr decreases by 18.55 mmol·kg^{-1} (wet weight) in the transition from rest to exhaustion in a maximally working muscle mass equal to 30% of M_b (body mass, kg), and τ (s) is the time constant of PCr splitting at the onset of exhausting exercise, assumed to be equal to the time constant (22.7-s) of the $\dot{V}O_2$ on-response at the muscle level.[18] $E_{an,al}$ (kJ) was calculated by assuming an energy equivalent of 0.468 kJ·mol^{-1} and a P/O_2 ratio of 6.25.[17]

Anaerobic lactic energy contribution ($E_{an,lac}$, kJ) was calculated as the energy derived from the net rate of lactate production by the working muscles:[15,17,19]

$$E_{an,lac} = \beta \, [La]_{b,net} \cdot M_b \quad (3)$$

where β is the energy equivalent of accumulated blood lactate, assumed to be 0.0689 $kJ \cdot mmol^{-1} \cdot kg^{-1}$,[19] $[La]_{b,net}$ is the net lactate concentration in blood ($mmol \cdot l^{-1}$), assuming a resting value of 1.5 $mmol \cdot l^{-1}$, and M_b (kg) is the swimmer's body mass.

Aerobic energy contribution (E_{aer}, kJ) to exercise during time t (s) was calculated from the time integral of $\dot{V}O_2$ versus exercise time according to a first-order kinetic function at the onset of exercise: [2,15,16,17]

$$E_{aer} = \alpha \dot{V}O_{2(t)} - \alpha \dot{V}O_{2(t)} \cdot \tau \left(1 - e^{-t/\tau}\right) \quad (4)$$

where α is the energy equivalent for O_2, assumed to be 20.9 $kJ \cdot l^{-1}$. $\dot{V}O_2$ ($l \cdot s^{-1}$) is the O_2 uptake, and $\dot{V}O_{2(t)}$ ($l \cdot s^{-1}$) is the $\dot{V}O_2$ measured at time t for each fraction of distance: 25-, 50-, 75- and 100-m. The second term of the equation represents the O_2 debt incurred at the onset of exercise.[17] The individual time constants of the on-transient of $\dot{V}O_2$ from rest to maximal exercise in time t were calculated by adjusting the data using a mono-exponential function: $\dot{V}O_{2(t)} = A_0 + A_1 \cdot \tau \left(1 - e^{-t/\tau}\right)$ where t(s) is the time from the onset of exercise, A_0 is the baseline, A_1 is the asymptotic amplitude of the exponential term, and τ (s) is the time constant. The time delay for the primary component was not taken into account and was excluded from the curve fitting procedure. Equations were fitted to the exercise data using the Marquardt-Levenberg algorithm iteratively until the differences between the residual sums of squared errors no longer decreased significantly. The Akaike information criterion was used to choose the best fit of the model to the data.[18] The $E_{an,al}$, $E_{an,lac}$ and E_{aer} contributions for each lap were then calculated as the difference in these three terms before and after each lap.[19] For the whole 100-m, the alactic anaerobic, lactic anaerobic and aerobic powers [$E_{an,al}$, $E_{an,lac}$ and E_{aer} (kW] were calculated by dividing the total energy (kJ) by the 100-m time.

Statistical Analysis

The normality of the distribution and homogeneity of variance were checked. The performance expressed in FINA points was considered a continuous variable and coded into two categories: swimmers who competed at the regional level Reg group (Reg, n = 23, ≤550 points and swimmers who competed at the national and international levels Nat-Int group (Nat-Int, n = 26, >550 points, with 550 being the median value of the normal performance distribution. Age was coded into two categories: ≤18 years old (Junior, n = 26) and >18 years (Senior, n = 23).

A stepwise multiple regression was applied to the dependent physiological variables one by one to quantify the effects of each of the three independent variables: age and performance level (continuous variables), and stroke style (coded from 1 to 4 for freestyle, backstroke, butterfly and breaststroke). For each model, the independence and normality of the residuals were verified. Subsequently the physiological variables were taken one by one and compared according to age, performance level and stroke style by one-way ANOVA. When the distributions were not normal (Kolmogorov Smirnov's test), Kruskal-Wallis and Mann-Whitney tests were used. Precision of the estimation was indicated with a 90% confidence interval. For all tests, significance was fixed at $p<0.05$. All tests were performed using R 3.3.3 (The R Foundation).

RESULTS

Table 1 shows the anthropometric and performance characteristics of the four subgroups of male swimmers.

O_2 uptake and swimming performance

For all groups $\dot{V}O_2$ increased by 19% (15; 24%) [mean (90% CI)] from L_{0-25} to L_{25-50} ($p<0.01$) and then stabilized in L_{50-75} and L_{75-100} . $[La]_{b,net}$ increased gradually from lap to lap ($p<0.01$) (Figure 1 a, upper panel).

The lap times and stroke rates over each 25 m measured during the 25- to 75-m laps were the same as for the 100-m time trial. In the isolated trials (Figure 1 b, middle panel), the swimming speed decreased 17% ± 7% from laps L_{0-25} to L_{25-50} ($p<0.01$) and 4% ± 5% from L_{50-75} to L_{75-100} ($p<0.01$). Stroke rate decreased from lap L_{0-25} to L_{25-50} ($p<0.01$). Percentage decreases for speed were [mean (90% CI)]: -17% (-15; -18%) from 25 to 50 m, -0.5% (-2; 1%) from 50 to 75 m, and -4% (-3; -5%) % from 75 to 100 m. The stroke rate decreased in similar fashion: -7% (-5; -9%) from 25 to 50 m and -0.9% (-3; 1%) from 50 to 75 m.

Metabolic energy estimates

$E_{an,al}$ (kJ) decreased from L_{0-25} to L_{75-100} (12 ± 2, 8 ± 1, 4 ± 1, 2 ± 1 kJ, mean ± SD, all $p<0.01$), whereas E_{aer} increased from L_{25-50} to L_{75-100} (13 ± 4, 23 ± 3, 25 ± 3 kJ, $p<0.01$). $E_{an,lac}$ was similar across laps (12 ± 7, 13 ± 9, 12 ± 9, 13 ± 9 kJ). As a result, E_{tot} decreased from L_{0-25} to L_{25-50} (39 ± 7 vs. 34 ± 10 kJ, $p<0.05$), increased for L_{25-50} and L_{50-75} (34 ± 10 vs. 39 ± 9 kJ, $p<0.01$), and then stabilized for L_{50-75} and L_{75-100} (39 ± 9; 40 ± 9 kJ). Figure 1 c, lower panel shows the relative contribution of each energy system (%E_{tot}) lap by lap during the 100 m. $E_{an,al}$ decreased from length to length ($p<0.05$), whereas E_{aer} increased substantially up to 75 m ($p<0.05$). $E_{an,lac}$ remained stable up to L_{75-100}.

Performance was 15% lower in freestyle swimmers compared with backstrokers ($p<0.05$; Table 2). The breaststroke swimmers also had lower energy expenditures and power outputs than the freestyle and backstroke swimmers.

The relative impact of each predictor (age, performance level, stroke style) on the dependent physiological variables is shown in Tables 3 and 4. E_{tot} and all the other metabolic energy predictors in absolute values (kJ) were strongly associated with age. Higher and more stable relationships were evident between performance level and $\dot{V}O_2$ ($\beta = 0.49, 0.91, 0.68$ for L_{0-25}, L_{25-}

$_{50}$, $L_{50\text{-}75}$, $p<0.05$). The regression equations for alactic anaerobic, lactic anaerobic and aerobic power (kW) were: $E_{an,al}$ (kW)=0.45*Age-0.43*Spe+0.33*Perf, $r^2adj=0.78$, $p<0.01$; $E_{an,lac}$ (kW)=-0.36Spe+0.37*Age, $r^2adj=0.34$, $p<0.01$; and E_{aer} (kW)=0.66*Perf, $r^2adj=0.31$, $p<0.01$.

Differences in the metabolic indices were evident by age and performance level (Tables 5 and 6). $[La]_{b,net}$, $\dot{V}O_2$, $E_{an,al}$ and $E_{an,lac}$ in absolute values were all substantially higher in Seniors ($p<0.05$). Similarly, when expressed as $\%E_{tot}$, Senior swimmers had higher $E_{an,lac}$ ($p<0.05$) and lower E_{aer} ($p<0.05$) energy contributions than Junior swimmers (Figure 2). The Nat-Int group had higher $[La]_{b,net}$, $\dot{V}O_2$, E_{tot} and absolute $E_{an,al}$ and $E_{an,lac}$ values, and higher relative (%) $E_{an,lac}$ but lower E_{aer} compared with the Reg swimmers (Figure 3).

DISCUSSION

This study measured physiological responses and the absolute and relative metabolic contributions in conditions similar to those of a competitive 100-m event by fractioning this distance into four 25-m laps swum at 100-m speed. We expected and confirmed that total energy expenditure and the absolute and relative contributions of the metabolic pathways vary substantially with age and performance level. Senior and Nat-Int swimmers typically exhibited higher absolute $\dot{V}O_2$ and alactic anaerobic, lactic anaerobic and E_{tot} production than younger and lower-level (Reg) swimmers. Faster performances were associated with higher $\dot{V}O_2$ and aerobic power.

For the whole group, the $\dot{V}O_2$ values (4.2 ± 0.8 l·min^{-1}) were similar to those observed in swimmers of similar level performing the same type of trial,[2,17,20] but higher than those measured in less efficient swimmers.[3,6] $[La]_b$ levels observed at the end of the 100 m were also similar to those observed previously.[2,18] Swim speed and stroke rate decreased throughout the 100-m trial, as observed in other 100-m time trials swum in competition conditions.[21] In parallel with these reductions, E_{tot} increased between 25 and 50 m but then decreased markedly by ~20% in the last 50 m compared with the first 50 m. This change is likely related to the rapid decrease of $E_{an,al}$ (muscle PCr is depleted in ~10-s) and the fast $\dot{V}O_2$ kinetics.[16,19] This pattern is consistent with the adaptive dynamics of the metabolic energy chains generally observed during supramaximal exercise of similar duration.[1]

Our data showed that $\dot{V}O_2$ increased rapidly and reached its maximal value at ~50 m. The $\dot{V}O_2$ kinetics from the first 30-s of exercise (up to 4.2 ± 0.7 $l \cdot min^{-1}$) appeared faster than that observed by Jalab et al.[5] in swimmers with a lower performance level who only reached their peak $\dot{V}O_2$ after 75 m. The time constant for $\dot{V}O_2$ kinetics was equal to or less than 10-15-s, consistent with the fastest values observed in previous studies.[16,19] The high swimming speed of the faster swimmers in our study induced rapid adjustment of $\dot{V}O_2$, with a near maximal fraction of $\dot{V}O_2$ reached quickly. This time course of $\dot{V}O_2$ increase has also been observed in other sports during all-out testing.[22] The $\dot{V}O_2$ kinetics are more rapid as exercise intensity increases, especially in the case of sustained elevations in $[La]_b$.[22] Moreover, the first 25 m was performed substantially faster than in Jalab et al.'s study[6] and in other studies conducted without the dive start, leading to a much higher energy demand.

E_{aer} was highest for breaststroke and ranged from ~46 to 58%E_{tot} (Table 2), which is slightly higher than the estimations reported by Capelli et al. (~33 to 46.5% for 91.4 m),[2] Ogita (~50% for 1-min swims),[23] and Rodríguez and Mader (54% and 41%, for 100 m using metabolic simulation).[1,5] These discrepancies are likely attributable to differences in swim speeds (higher in the swimmers of this study, which comprised 4 Olympic medallists), methodologies and protocols, and/or different pool lengths (25-m versus 50-m pool) and bout durations. The anaerobic contribution calculated in this study was ~49%, consisting of ~18% from $E_{an,al}$ and ~31 from $E_{an,lac}$.

In other studies, the total anaerobic relative contribution was ~48% in high-level swimmers[1] and ~57% in 17 well-trained junior swimmers,[4] whereas Ogita[23] reported 50% for a maximal 1-min bout.

Up to 75 m, the E_{aer} and $E_{an,al}$ dynamics followed the established model of energy system coupling during supramaximal exercise.[1,15,25] From the beginning to the end of the 100 m, the $E_{an,al}$ contribution decreased and the E_{aer} contribution increased, whereas the $E_{an,lac}$ contribution was stable. This stabilization does not concord with the 50% increase in the power of this metabolic pathway between 10- and 40-s usually reported for 1-min maximal exercise bouts.[15] It appears that the swimmers in our study controlled their pace so as not to over-solicit anaerobic glycolysis. Effective pacing might attenuate the reductions in power output and stroke length towards the end of the race.[26]

The senior swimmers showed higher peak $[La]_b$, $\dot{V}O_2$ and energy expenditure levels. In males, anthropometric changes in puberty are associated with enhanced energy potential (increases in height, muscle and total mass, and strength and anaerobic power).[11] For the same energy cost, the increases in metabolic capacities that occur during puberty improve performance. This enhanced energetic capacity is greater in athletic subjects than sedentary individuals,[10] and continues after the end of puberty in high-level athletes provided that training loads and volume are increased progressively.[27] The increase in anaerobic contribution for the older swimmers confirms the pubertal shift in metabolism towards higher reliance on glycolytic motor units.[9]

Stepwise multiple regression showed a substantial relationship between 100-m freestyle performance and maximal aerobic potential ($\dot{V}O_2$ in both absolute and mass-related values and the aerobic power obtained by dividing E_{aer} by the performance time). High aerobic energy potential was identified as a performance discriminator in medium- and long-distance endurance sports.[27] In swimming, the importance of maximal aerobic potential for fast performances has been widely debated. Although some investigators have reported that $\dot{V}O_{2peak}$ or $\dot{V}O_{2max}$ are good performance predictors for swimming performance,[12,14,28] others failed to identify this relationship.[24] As confirmed by our results, this mixed picture indicates that many metabolic processes and factors interact,[25] which may obscure the importance of aerobic energy production.[14]

The highest value of $\dot{V}O_2$ was reached as early as 50 m for the fastest swimmers but only in the last 25 m for the slowest. Elite swimmers show a remarkably rapid adjustment in $\dot{V}O_2$, which allows them to decrease the amplitude of the oxygen debt and reduce their dependence on anaerobic glycolysis at the start of the swim.[28] The rapid adjustment of $\dot{V}O_2$ is an index of the oxidative potential,[22] which has been related to aerobic potential and performance in swim trials.[28] The rapid increase in $\dot{V}O_2$ contrasts with studies reporting a continuous increase to the end of the 100 m.[2,4,16,24] Again, the swim speed, type of pacing, and trial conditions probably account for the differences. For the fastest swimmers, the speed in the first 25 m was higher than the values reported in other studies, which may explain the more rapid rise in $\dot{V}O_2$. Moreover, the decline in speed over the last three 25-m lengths (8%) was greater than in the studies carried out at constant speed, [2,4,16,24] which might explain the $\dot{V}O_2$ stabilization compared with the continuous increase in other studies. The results of our study do not support the assertion that the decline in $\dot{V}O_2$ at the end of the trial relates to inhibition of mitochondrial activity caused by excessive acidosis or depletion of phosphocreatine stores.[29] Measured $[La]_b$ values <13 $mmol\cdot l^{-1}$ in the oldest and fastest swimmers were much lower than the ~18-20 $mmol\cdot l^{-1}$ typically found in 100-m sprinters. Although $[La]_b$ and anaerobic expenditure were similar in faster and slower swimmers, the latter showed a continuous rise in $\dot{V}O_2$ throughout the trial. Nevertheless, it is likely that the increase in muscle lactate concentration contributed to a decline in power output, stroke length and swim speed at the end of the 100 m.[19,21]

The contribution of maximal aerobic metabolism to 100-m swimming performance is discernable at two levels. First, the $\dot{V}O_2$ during the 100-m trial reached 94-100% of $\dot{V}O_{2max}$ from the 50-m. Rapid $\dot{V}O_2$ kinetics meant a lower oxygen debt at the start of the trial. Secondly, aerobic contribution for the entire 100 m accounted for ~48-53%, indicating that this system provided the most energy of the three metabolic systems. In the multiple regression equations, E_{aer} (kW) was associated with the fastest performances, contrary to $E_{an,lac}$ (kW). These differences most likely relate to differences in maturation, height and mass in the two groups.[10,11]

An obvious limitation of this study is the fractionated approach. As in real competition, the four lengths were swum in different conditions, with the first 25 m having a dive start and the third after a tumble turn. This was compensated by pacing the shorter sprints (25 to 75 m) to the maximal speed attained at the initial 100-m trial. We also chose to estimate $\dot{V}O_2$ from the 20-s average measured during recovery, a previously validated technique,[4] and the common method used by the French Swimming Federation. However, Chaverri et al. showed that this method underestimates exercise values by ~4.5% in a 200-m trial.[30] It can nevertheless be assumed that the faster $\dot{V}O_2$ off-kinetics after the 100-m swim compared with a 200-m trial would have partially compensated for this bias.

PRACTICAL APPLICATIONS

The information obtained in this study should be useful for determining the metabolic capacities of elite junior and senior swimmers. Specifically, in designing training programs during the pubertal period, coaches need to consider the large increase in anaerobic power, the small increase in aerobic capacities, and the metabolic shift towards a higher relative anaerobic contribution characteristic of senior male swimmers.

CONCLUSIONS

Measurement of gas exchange and blood lactate concentration at the end of every lap of a 100-m trial (25, 50, 75-m) conducted under competition conditions yielded contributions from the alactic anaerobic (~18%), aerobic (~51%) and lactic anaerobic (~31%) systems. Over the course of the 100-m swimming time trial, the relative alactic contribution decreased, the aerobic contribution increased up to 100 m, and the lactic anaerobic contribution remained stable, indicating pacing control. Older swimmers exhibited higher $\dot{V}O_2$, blood lactate concentration and total, alactic and lactic energy expenditures. The performances of the fastest swimmers were related to the indices of oxidative potential: high $\dot{V}O_2$, aerobic power and less time to reach the highest $\dot{V}O_2$ at about 50 m.

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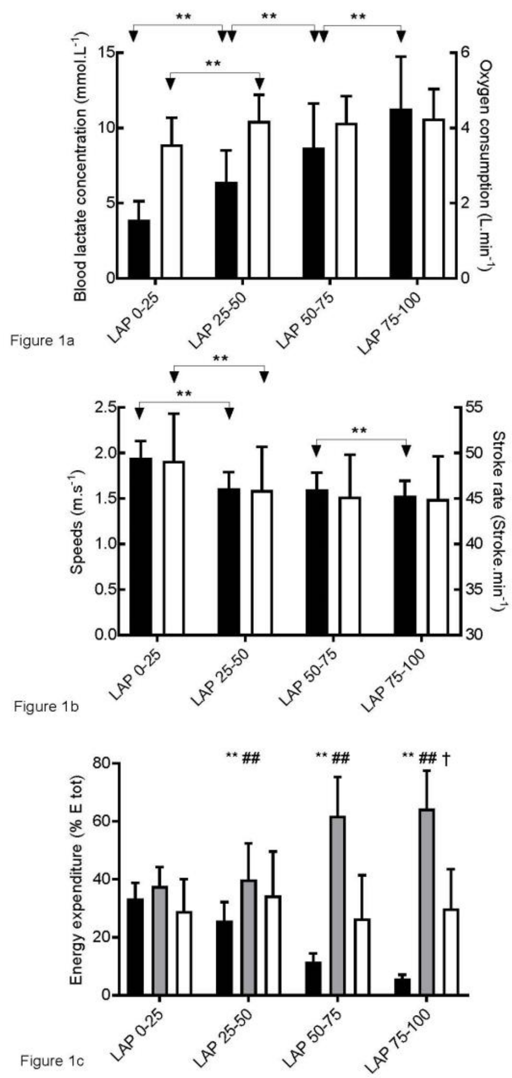

Figure 1. Upper panel (1 a), blood lactate concentration (black columns) and oxygen consumption ($\dot{V}O_2$) (white columns with black outlines), changes over the four lengths of the 100-m time trial for the whole group of swimmers (mean ± SD). Middle panel (1 b), speed (black columns) and stroke rate (white columns with black outlines) changes over the four lengths of the 100-m time trial for the whole group of swimmers (mean ± SD). Significant differences between laps are indicated with * for $p<0.05$ and ** for $p<0.01$. Lower panel (1 c), metabolic energy relative contribution (%E_{tot}) for the four swimming laps in the whole group of swimmers: alactic anaerobic (black), aerobic (grey with black outline), lactic anaerobic (white with black outline) (mean ± SD). For each energy system, significant differences with the previous lap are indicated with * for alactic anaerobic, # for aerobic and † for lactic anaerobic. *, #, † for $p<0.05$ and **, ##, †† for $p<0.01$.

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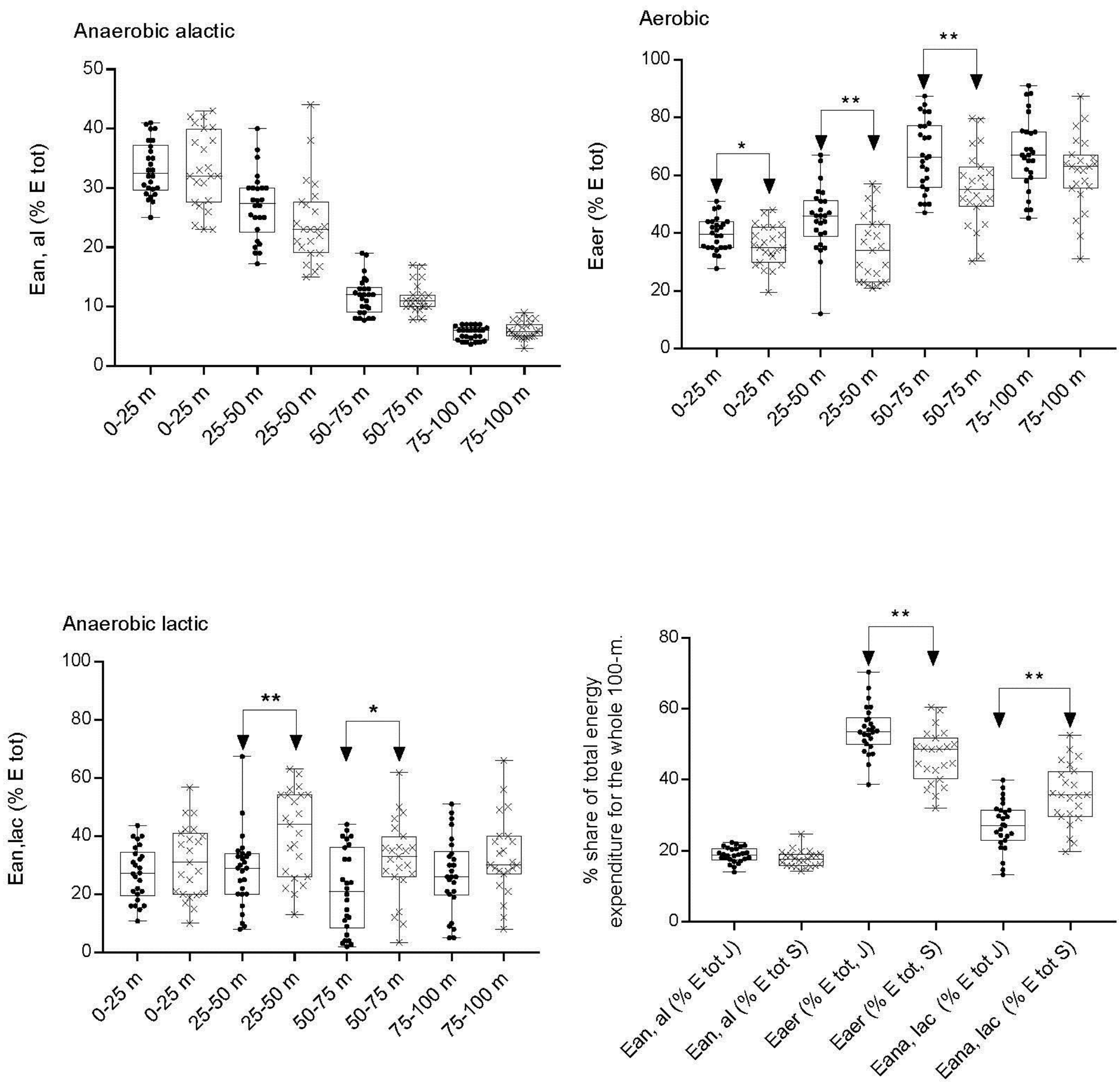

Figure 2. Comparing metabolic energy relative contribution (%E_{tot}) between juniors swimmers (Box-Whiskers plots with black points, median and 25th and 75% percentile and the bars the highest and lowest values) and senior swimmers (Box-Whiskers plots with black crosses). Comparisons across both groups for alactic anaerobic (upper left), lactic anaerobic (lower left), aerobic (upper right). Bottom right, energy relative contribution (%E_{tot}) of junior and senior swimmers for the whole 100 m. For each energy system, significant differences between the slowest and the fastest swimmers are indicated with *for $p<0.05$ and ** for $p<0.01$.

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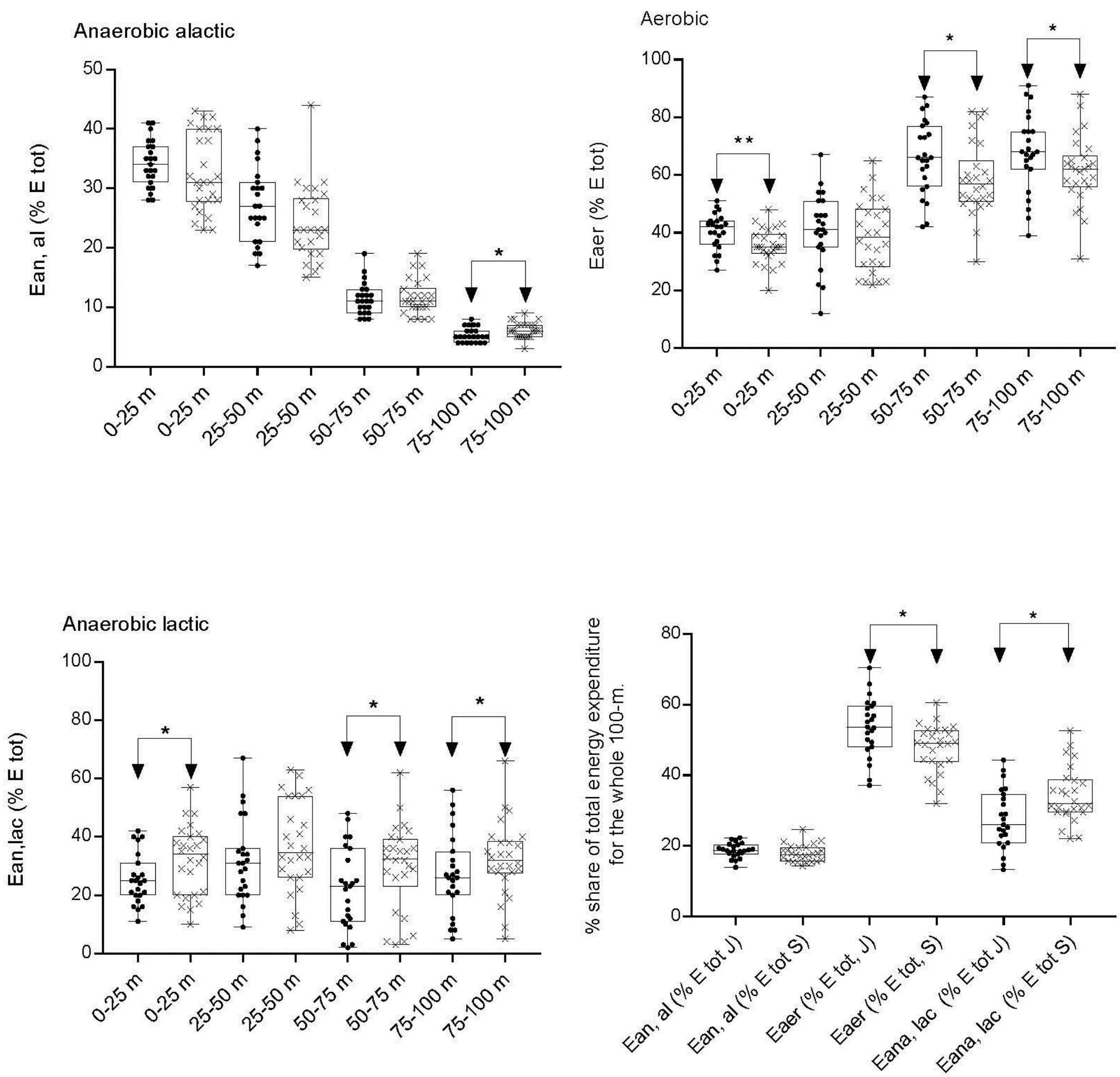

Figure 3. Comparing metabolic energy relative contribution (%E_{tot}) between the slowest swimmers (Reg group) (Box-Whiskers plots with black points, median and 25th and 75% percentile and the bars the highest and lowest values) and fastest swimmers (Nat-Int) (Box-Whiskers plots with black crosses). Comparisons across both groups for alactic anaerobic (upper left), lactic anaerobic (lower left), and aerobic (upper right). Bottom right, energy relative contribution (%E_{tot}) of slowest and fastest swimmers for the whole 100 m. For each energy system, significant differences between the slowest and the fastest swimmers are indicated with *for $p<0.05$ and ** for $p<0.01$.

Table 1: Subject characteristics categorized for age and performance level (n=49). Level of performance was determined by the FINA points score (pts) for comparison of swimmers across different events.

Age Junior (top row, n=26) vs. Senior (bottom row, n=23)				**Performance level** Reg (top row, n=23) vs. Nat-Int (bottom row, n=26)			
Age (years)	Level (pts)	Mass (kg)	Height (cm)	Age (years)	Level (pts)	Mass (kg)	Height (cm)
16 ± 1	519 ± 77	65 ± 8	178 ± 8	18 ± 4	479 ± 54	67 ± 10	180 ± 9
24 ± 5	629 ± 124	78 ± 8	188 ± 7	22 ± 6	652 ± 101	77 ± 8	186 ± 7

Data are mean ± SD. Subjects were categorized in four groups: Junior (≤18 years), Senior (>18 years), Reg (≤550 FINA pts) and Nat-Int (>550 FINA pts).

Table 2: Performance level, age, peak oxygen uptake, and metabolic energy contribution, energy share and power according to swimming stroke.

	Freestyle (n=25)	**Backstroke** (n=8)	**Butterfly** (n=8)	**Breaststroke** (n=8)
Performance level (FINA pts)	560 ± 109*	643 ± 100	554 ± 83	578 ± 200
Age (years)	20 ± 6	21 ± 4	19 ± 2	21 ± 7
$\dot{V}O_2$ ($l \cdot min^{-1}$)	4.2 ± 0.9	4.5 ± 0.5†	4.1 ± 0.7	4.2 ± 0.8
$\dot{V}O_2/M_b$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	58 ± 1	62 ± 9	60 ± 10	62 ± 7
$[La]_{b,net}$ ($mmol \cdot l^{-1}$)	11.6 ± 3.3	13.9 ± 3.8##	10.9 ± 2.2#	7.9 ± 2.1
$E_{an,al}$ (kJ)	27± 3	28 ± 2†	26± 2	27 ± 4
$E_{an,lac}$ (kJ)	46 ± 20#	64 ± 21#†	43 ± 12	32 ± 15
E_{aer} (kJ)	79 ± 9#	76 ± 5	79 ± 10	85 ± 11
E_{tot} (kJ)	153 ± 22	168 ± 22#†	147 ± 16	144 ± 24
$E_{an,al}$ (% E_{tot})	18 ± 2	17± 2	17 ± 1	19 ± 2
$E_{an,lac}$ (% E_{tot})	29 ± 9##	37± 8##	29 ± 6#	32 ± 15
E_{aer} (% E_{tot})	53 ± 8#	46 ± 7#†	54 ± 6	58 ± 7
P_{tot} (kW)	2.6 ± 0.6#	2.8 ± 0.5#	2.4 ± 0.3	2 ± 0.6
$P_{an,al}$ (kW)	0.5 ± 0.1#	0.5 ± 0.05	0.4 ± 0.05	0.4 ± 0.1
$P_{an,lac}$ (kW)	0.9 ± 0.4#	1 ± 0.4†##	0.7 ± 0.23#	0.5 ± 0.3
P_{aer} (kW)	1.25# ± 0.16	1.25 ± 0.1	1.3 ± 0.2	1.2 ± 0.2

Data are mean ± SD. Significance of the differences in distribution tested with Mann-Whitney U-test ($p<0.05$): * for differences with backstroke; † for differences with butterfly; # for differences with breaststroke. **, ††, ## with $p<0.01$.

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Table 3: Multiple regression coefficients between the three independent variables (age, performance level, and stroke specialty) and the dependent variables $[La]_b$, absolute $\dot{V}O_2$ and mass-related $\dot{V}O_2$ for each swimming length.

	Age (years)					**Performance level** (FINA points)					**Stroke specialty** (free 1, back 2, fly 3, breast 4)				
Length (m) →	0-25	25-50	50-75	75-100	100	0-25	25-50	50-75	75-100	100	0-25	25-50	50-75	75-100	100
$[La]_{b,net}$ ($mmol^{\cdot l-1}$)			0.32* (0.06, 0.57)									–0.29* (-0.54,–0.03)		–0.32* (-0.67,–0.05)	
$\dot{V}O_2$ ($l{\cdot}min^{-1}$)				0.57** (0.33, 0.80)		0.49** (0.16, 0.63)	0.91** (0.59, 1.22)	0.68** (0.48, 0.87)							
$\dot{V}O_2/M_b$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)		–0.77** (–1.14, –0.39)					0.80** (0.42, 1.17)	0.57** (0.15, 0.98)							

Data are β coefficients and associated 95% confidence intervals (in parentheses) obtained from the stepwise multiple regression equations between the dependent variables considered one by one (net [La]s, absolute $\dot{V}O_2$ and mass-related $\dot{V}O_2$ at each 25-m length) and the independent variables (age, performance and swimming stroke). The values of the regression coefficients are given with all independent variables considered to be equal.

Only significant variables are presented for each regression coefficient. The residuals were normally distributed. * for $p<0.05$ and ** for $p<0.01$.

Table 4: Multiple regressions coefficients between the three independent variables (age, performance level and stroke specialty) and the dependent variables E_{tot}, $E_{an,al}$, $E_{an,lac}$ and E_{aer}, in both absolute and relative values, for each swimming lap.

	Age (years)					**Performance level** (FINA points)					**Stroke specialty** (free 1, back 2, fly 3, breast 4)				
Length (m) →	0-25	25-50	50-75	75-100	100	0-25	25-50	50-75	75-100	100	0-25	25-50	50-75	75-100	100
E_{tot} (kJ^{-1})		0.58** (0.35,0.81)	0.49** (0.24,0.74)		0.51** (0.39,0.63)				0.28* (0.01,0.55)						
$E_{an,al}$ (kJ^{-1})	0.50** (0.25,0.74)	0.82** (0.49,1.1)	0.49** (0.22,0.76)	0.53** (0.31,0.75)	0.67** (0.46,0.88)			0.26* (0,0.54)	0.26* (0.04,0.47)				-0.35* (-0.53,-0.17)	-0.48** (-0.33,-0.62)	-0.42** (-0.63,-0.21)
$E_{an,lac}$ (kJ^{-1})			0.55** (0.32,0.78)	0.68** (0.31,1.05)	0.44** (0.19,0.68)						-0.30* (-0.54,-0.05)				
E_{aer} (kJ^{-1})				0.30* (0.10,0.49)						0.22* (0.01,0,27)	0.53** (0.28,0.77)		0.50** (0.25,0.74)	0.43** (0.20,0.66)	0.45** (0.19,0.70)
$E_{an,al}$ ($\%E_{tot}$)	0.50* (0.09,0.91						–0.33* (-0.07,-0.58)						-0.28* (-0.01,-0.55)		
$E_{an,lac}$ ($\%E_{tot}$)		0.45** (0.21,0.72)	0.60** (0.22,0.98)		0.38** (0.13,0.61)						–0.38** (-0.12,-0.64)			–0.36** (-0.63,-0.08)	–0.43** (-0.19,-0.66)
E_{aer} ($\%E_{tot}$)		–0.56** (-0.97,-0.17)	-0.48** (-0.25,-0.71)		-0.40** (-0.62,-0.18)						0.50** (0.37,0.62)		0.31* (0.08,0.54)	0.41** (0.15,0.67)	0.48** (0.26,0.71)

Data are β coefficients and associated 95% confidence intervals obtained from the stepwise multiple regression equations between the dependent variables considered one by one (E_{tot}, $E_{an,al}$, $E_{an,lac}$ and E_{aer}, in both absolute values and relative to total energy expenditure ($\%E_{tot}$) for each 25-m length), and the independent variables (age, performance, stroke specialty).The values of the regression coefficients are given for one given independent variable with all other independent variables considered to be equal. Only significant variables are presented for each regression coefficient. The residuals were normally distributed. * for $p<0.05$ and ** for $p<0.01$.

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Table 5: Net blood lactate concentration ($[La]_b$), $\dot{V}O_2$ absolute ($l \cdot min^{-1}$) and relative to body mass ($ml \cdot kg^{-1} \cdot min^{-1}$) for each swimming length according to age (top panel) and performance level (bottom panel).

	Junior (≤ 18 years, n = 26)				**Senior** (> 18 years, n = 23)			
Length (m) →	0-25	25-50	50-75	75-100	0-25	25-50	50-75	75-100
$[La]_{b,net}$ ($mmol \cdot l^{-1}$)	3.7 ± 0.9	5.9 ± 1.7	7.7 ± 2.2	9.9 ± 2.3	4.1±1.5	7.3 ± 2.3*	10.1 ± 3.2**	12.9 ± 3.7**
$\dot{V}O_2$ ($l \cdot min^{-1}$)	3.3 ± 0.7	3.9 ± 0.7	3.8 ± 0.6	3.8 ± 0.8	3.8 ± 0.7*	4.5 ± 0.6**	4.5 ± 0.7**	4.6 ± 0.6**
$\dot{V}O_2/M_b$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	50 ± 10	59 ± 10	57 ± 9	58 ± 12	50 ± 9	59 ±11	59 ± 9	61 ± 10
	Reg (≤550 FINA points, n = 23)				**Nat-Int** (>550 FINA points, n = 26)			
Length (m) →	0-25	25-50	50-75	75-100	0-25	25-50	50-75	75-100
$[La]_{b,net}$ ($mmol \cdot l^{-1}$)	3.6 ± 0.8	6.1 ± 2.1	8.0 ± 2.7	10.3 ± 3.1	4.2 ± 1.4*	6.9 ± 2.2	9.4 ± 3.1*	12.3 ± 3.5*
$\dot{V}O_2$ ($l \cdot min^{-1}$)	3.2 ± 0.6	3.7 ± 0.5	3.7 ± 0.5	3.9 ± 0.9	3.9 ± 0.6**	4.6 ± 0.5**	4.5 ± 0.6**	4.5 ± 0.7**
$\dot{V}O_2/M_b$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	48 ± 10	56 ± 10	56 ± 8	59 ± 12	51 ± 9	61 ± 9#	60 ± 10#	60 ±11

Data are means and standard deviation according to age (Junior ≤18, Senior >18 years) and performance level (Reg ≤550, Nat-Int >550 FINA points). The significance of the differences in distribution was tested with the Student's t-test when the distributions were normally distributed, and with a Mann-Whitney U-test otherwise. Significant * for $p<0.05$ and ** for $p<0.01$; # for $p=0.08$, nonsignificant.

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Table 6: Estimated absolute (kJ) and relative (%E_{tot}) metabolic energy contribution according to age (top panel) and performance level (bottom panel) for each swimming lap.

	Junior (≤18 years, n = 26)					**Senior** (>18 years, n = 23)				
Length (m) →	0-25	25-50	50-75	75-100	100	0-25	25-50	50-75	75-100	100
E_{tot} (kJ)	37 ± 6	30± 6	35 ± 9	36± 6	138 ± 18	41 ± 8*	39 ± 11**	43 ± 9**	45 ± 11**	168 ± 26**
$E_{an,al}$ (kJ)	12 ± 1	8 ± 1	4 ± 1	2 ± 1	27 ± 3	13 ± 1**	9 ± 1**	5 ± 12**	3 ± 1**	30 ± 3**
$E_{an,lac}$ (kJ)	10 ± 5	9 ± 5	9 ± 7	10 ± 6	38 ± 12	14 ± 8	17 ± 10**	15 ± 9**	16 ± 11**	62 ± 24**
E_{aer} (kJ)	14 ± 2	13± 5	22 ± 4	24 ± 4	73 ± 13	14 ± 2	13 ± 4	23 ± 3	26 ± 2	76 ± 8*
	Reg (≤550 FINA points, n = 23)					**Nat-Int** (>550 FINA points, n = 26)				
Length (m) →	0-25	25-50	50-75	75-100	100	0-25	25-50	50-75	75-100	100
E_{tot} (kJ)	35 ± 5	32 ± 8	36 ± 9	37± 8	138 ± 29	42 ± 8**	37 ± 11*	42 ± 10*	43 ± 10**	164 ± 25**
$E_{an,al}$ (kJ)	12 ± 1	8 ± 1	4 ± 1	2 ± 1	26 ± 3	13 ± 1**	9 ± 1**	5 ± 1**	3 ± 1**	29 ± 3**
$E_{an,lac}$ (kJ)	9 ± 4	11± 7	9 ± 7	10 ± 8	39 ± 18	14 ± 8*	15 ± 10	14 ± 9	15 ± 10*	58 ± 22**
E_{aer} (kJ)	14 ± 2	13 ± 5	22 ± 3	24 ± 4	73 ± 12	14 ± 2	14 ± 4	23 ± 3	26 ± 3	77 ± 9

The significance of the differences in distribution was tested with the Student's t-test when the distributions were normally distributed and with a Mann-Whitney U-test otherwise. E_{tot} (kJ) for total energy in kilojoules, $E_{an,al}$ (kJ) for alactic anaerobic energy in kilojoules, $E_{an,lac}$ (kJ) for lactic anaerobic energy in kilojoules, E_{aer} (kJ) for aerobic energy in kilojoules.