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CASE STUDY

Maturation to elite status: a six-year physiological case study of a world champion rowing crew

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Abstract This case study reports the results of a 6-year (2005–2010) follow-up study of a world-class rowing crew, the current world champions. The rowers were 15–16 years old and prospective competitors at the junior level when the study began in 2005, and we monitored their physical, physiological, and rowing ergometer performance data annually. Our findings indicated that over the 6-year period gains in stature, averaged across rowers, amounted to only +2 cm (+1%). In contrast, body mass increased by +9 kg (+10%) and fat-free mass by +11 kg (+15%). A significant linear trend ($R^2 = 0.998$, $P < 0.001$) and a +26% increase in maximal oxygen uptake (in L min^{-1}) was evident from 2005 to 2009, resulting in a leveling-off and a crew average of ~6.6 L min^{-1} (~70 mL kg^{-1} min^{-1}) during the last 2 years of assessment. Power output at anaerobic threshold increased by +23%, subsequently amounting to a crew average of 359 W in 2010. Oxygen uptake at anaerobic threshold, expressed as a percentage of maximal oxygen uptake, changed little and ranged between 82 and 85%. A curvilinear regression provided the best fit to describe the 6-year improvement (+7%) in 2000 m ($R^2 = 0.984$, $P < 0.001$) and 6000 m ($R^2 = 0.989$, $P < 0.001$) rowing ergometer performance times. Performance-related physical and physiological parameters seem to level-off at about 20 years of age, which may partly explain the corresponding stabilization in ergometer performance times over the last years of assessment.

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Introduction

Physiological studies over a multi-year period of world-class athletes who represent the true elites of their respective sports (e.g., Olympic and world champions) are rare, which is probably due to limited access to such subjects and also due to the finite nature of the population. Nevertheless, such case studies performed on top-caliber athletes in endurance events have been occasionally reported, perhaps most notably on a world champion long distance runner (Jones 1998) and a multiple Tour de France cycling race winner (Coyle 2005). In rowing, a 20-year follow-up study of 1972 Olympic medalists was conducted to examine the long-term changes in physiological profile of rowers following their competitive careers (Hagerman et al. 1996). More recently, a case study (Lacour et al. 2009) focused on an Olympic champion sweep-oar rower describing the physical and physiological data of an elite rower over 11 years. Both of these studies (Hagerman et al. 1996; Lacour et al. 2009) investigated periods of peak career performance and/or periods following cessation of competitive rowing training. However, the literature still lacks multi-year longitudinal data that would provide an insight into the world-class rowers' physiological and performance progress from maturation to elite status.

Rowing is typically described as a strength-endurance type of sport. During a 2000 m rowing race, which typically lasts 5.5–7.0 min depending on a boat type and whether conditions, anaerobic alactic and lactic as well as aerobic capacities are stressed to their maximum potential (Steinacker 1993). The total energy demands of a typical rowing race are estimated to be 70–80% aerobic and 20–30% anaerobic (Maestu et al. 2005). Therefore, the training of successful rowers has to be built up with a focus on aerobic training with proper relationship of strength training and anaerobic training. Endurance training eliciting a blood lactate concentration in the range of 2–4 mmol L^{-1} is the mainstay of success in rowing with 70–80% of the training time spent on the water (Maestu et al. 2005). Because of the particular importance of aerobic endurance for successful rowing, it comes as no surprise that maximal oxygen uptake ($\dot{V}O_{2max}$) in L min^{-1} and maximal aerobic power (in W) obtained during a progressive test to exhaustion frequently emerged as important parameters in predicting rowing performance as assessed by a simulated 2000 m race on a rowing ergometer (for review, see Maestu et al. 2005). However, while elite rowers spent most of their time training to enhance aerobic endurance, one of the main challenges in their training regimens is to simultaneously maintain the strength gains, as resistance training is one physical performance factor of a complete annual training program (Secher 1993).

Rowing ergometers are generally considered valuable tools for monitoring changes in performance capacity of rowers. Among elite rowers, all-out tests over 2000 and 6000 m distances performed on a rowing ergometer are frequently used for evaluation of their exercise capacity. The results of these tests often serve coaches as indicators of training status of their rowers and as one of the criteria whereby athletes are selected for national team crews. The purpose of the current study was: (a) to describe the physical, physiological, and performance characteristics of a world-class male heavyweight rowing crew; (b) to investigate changes caused by long-term rowing training using the aforementioned physical, physiological, and performance measurements and the relationships between these measures; and (c) to examine how changes in physiological function affect rowing performance.

Methods

This case study reports the results of a 6-year long study of a world-class rowing crew, the men's heavyweight quadruple-sculls, the current (as of 2010) world rowing champions, winners of the World Rowing Cup, and world "under-23" rowing champions. Three members of the crew were 16 years old, and one member was 15 years old when the study began in 2005. In addition to the aforementioned results achieved in 2010 at open class level, between 2006 and 2009 the studied rowers have, either as a crew or as members of other crews, won multiple medals at World Junior Rowing Championships (3 medals) and World Under-23 Rowing Championships (2 medals). Physical, physiological, and performance assessments completed at regular intervals throughout the study included stature, body mass, body composition, maximal oxygen uptake, anaerobic threshold, and 2000 and 6000 m rowing ergometer performance times. These measures were used to provide a comprehensive picture of adaptations in physical, physiological, and performance characteristics of rowers to long-term training.

The four studied rowers underwent annual physical and physiological assessments in our laboratory from 2005 to 2010. The assessment was performed during preparatory periods, either in December or early January. Exactly the same procedures and equipment were used for each testing session, and the same researcher performed the procedures for all rowers. The tests were always conducted in the morning hours, between 8:30 and 11 am. Before arriving at the laboratory, the rowers were instructed to (a) train only lightly in the 48 h preceding a test session, (b) have a light breakfast not less than 90 min prior to testing, and (c) be in a fully hydrated state when arriving at the laboratory. At each occasion, both oral and written informed consent was obtained following explanations of the procedures and the risks associated with participation, in accordance with the Helsinki Declaration. This study received approval from the Institutional Review Board.

Stature was measured to the nearest 0.01 m using an anthropometer (GPM, Zurich, Switzerland), and body mass was determined to the nearest 0.1 kg using a beam balance scale (Seca, Hamburg, Germany). The sum of seven skin folds was calculated to provide an estimate of fat mass (Jackson and Pollock 1978). Fat-free mass (FFM) was calculated by subtracting the estimated fat mass from the body mass. Following the anthropometric measurements, the rowers were given 10 min to warm-up by combining ergometer rowing (Concept 2 Model C, Morrisville, VT, USA) and stretching in accordance with their usual habits. The rowers were subsequently equipped with the necessary instrumentation and sat quietly for 1 min on the ergometer before starting the exercise. The exercise started at a work rate of 150 Watts (W), which the rowers maintained for 3 min. Subsequently, the rowers were required to increase the work rate incrementally by 25 W every minute until exhaustion. Each rower chose his optimal stroke rate for each work rate. The drag factor for all tests ranged between 120 and 125.

Gas-exchange data were measured breath-by-breath using a Quark b^2 metabolic measurement cart (Cosmed, Rome, Italy) and stored in the memory of a PC for later analysis. Before each test, the gas analyzers were calibrated using gases (CO_2 and O_2) of known concentration, and the flow meter was calibrated using a 3-L syringe. Heart rate was monitored using the short-range Polar radio telemetry system (Polar Electro, Kempele, Finland). The attainment of maximal oxygen uptake ($\dot{V}O_{2max}$) was verified by a plateau in oxygen uptake against exercise intensity and a value of respiratory exchange ratio ≥1.10. All rowers satisfied both criteria on all occasions. During off-line processing, data were averaged to 30-s intervals, and the highest values for physiological parameters were calculated as the highest mean of two consecutive 30-s intervals. Power at $\dot{V}O_{2max}$ (i.e., maximal aerobic power) was the mean of two consecutive 30-s intervals used for calculation of $\dot{V}O_{2max}$. Anaerobic threshold (AT) was determined non-invasively using the simplified V-slope method, as recommended by Meyer et al. (2005). The V-slope method allows detection of the anaerobic threshold based on accelerated rate of CO_2 output compared to oxygen uptake. When indeterminate, the V-slope method was supported with inspection of the respiratory exchange ratio, ventilation and ventilatory equivalents for O_2 and CO_2. When AT was detected as the first data point at any given stage, power output at AT was estimated as the mean value of the two closest power outputs. The determination of AT using the above-described methodology was performed by two independent, experienced observers and then compared. If the AT values differed, the AT was determined by consensus.

The 2000 and 6000 m rowing ergometer performance data were collected at competitions organized by the national rowing federation. Specifically, these competitions are held in January or early February of each year and not more than 6 weeks from physiological testing dates. All rowing ergometer performance times analyzed for the purpose of this study were achieved on stationary Concept II (model D) rowing ergometers. All reported data in the study are presented as mean (minimum value − maximum value) data.

Results and discussion

This case study describes the physical, physiological, and performance development of four heavyweight male rowers from age 15–16, when the athletes were prospective rowers at the junior level, to age 20–21, when the rowers had achieved full physical and physiological maturity and achieved world-class status by winning multiple world championship titles. It should be acknowledged that (a) over the 6-year period of the study the rowers competed exclusively in sculling boats on major competitions, and (b) from 2005 to 2008 they competed in various sculling boats; they formed a quadruple-scull squad in early 2009 and spent the rest of 2009 and entire 2010 competing together as a crew.

During 2005 and 2006, when the studied rowers competed at junior level, their stature was consistent with data reported for junior rowers competing in the 1997 World Junior Rowing Championship (Bourgois et al. 2000), but their body mass was 4–8 kg greater. Over the 6-year period, gains in stature for the studied crew amounted to only 2 cm (+1%), confirming the previous report (Jurimae et al. 2007) that stature from junior- to open-class level rowers increases only minimally. However, their body mass over the same 6-year period increased by about +9 kg (+10%), and even more dramatic increases were evident in fat-free mass: +11 kg (+15%). This is an important finding in terms of rowing performance given the well-established positive relationship between FFM and both 2000 m ergometer and on-water performance. From 2008 to 2010, the average estimated FFM amounted to ~86 kg and appeared to change very little, if at all. This observation is hardly surprising, given that in 2008 the studied rowers were 19 years old, i.e., the approximate age when physical growth is expected to end. The percentage of body fat displayed a slight, albeit constant decreasing trend, from 13.4% in 2005 to 9.4% in 2010. A relatively low percentage of body fat seems to be important for medal-winning performance on major competitions: the ~9% of body fat in the studied crew corroborates ~8% value reported for Olympic rowers (Jurimae et al. 2007).

Physiological measures indicated a steady improvement in $\dot{V}O_{2max}$, expressed both in absolute units as well as in ratio standard mass-related units, from 2005 to 2009 (Fig. 1). In fact, a significant linear trend ($R^2 = 0.998$, $P < 0.001$) is evident for an increase (+26%) in mean $\dot{V}O_{2max}$ value expressed in L min^{-1} between 2005 and 2009. Between 2009 and 2010 no apparent changes in $\dot{V}O_{2max}$ were evident and, although further annual monitoring is necessary, it appears likely that the rowers have neared the pinnacle of their potential, after which further substantial increases in $\dot{V}O_{2max}$ are difficult to achieve. The high mean value of ~6.6 L min^{-1} (~70 mL kg^{-1} min^{-1}; ~315 mL kg$^{0.67}$ min^{-1}) further supports this assumption, as do the findings of (a) Rusko (1987) who reported $\dot{V}O_{2max}$ in world-class cross-country skiers peaking at the age of 20, with no consistent subsequent change until the age of 25; and (b) Legaz Arrese et al. (2005), who reported a plateau in $\dot{V}O_{2max}$ in elite distance runners aged more than 20–22 years; this plateau subsequently lasted several years. Note that the highest recorded individual values for $\dot{V}O_{2max}$ in the monitored rowers amounted to 6.97 L min^{-1} in 2009 and 6.84 L min^{-1} in 2010. In comparison with other rowing champions, a 2000 Olympic champion sweep-oar rower recorded $\dot{V}O_{2max}$ of ~6.3 L min^{-1} at roughly the same time within a rowing season (i.e., in December) during the peak of his career (Lacour et al.

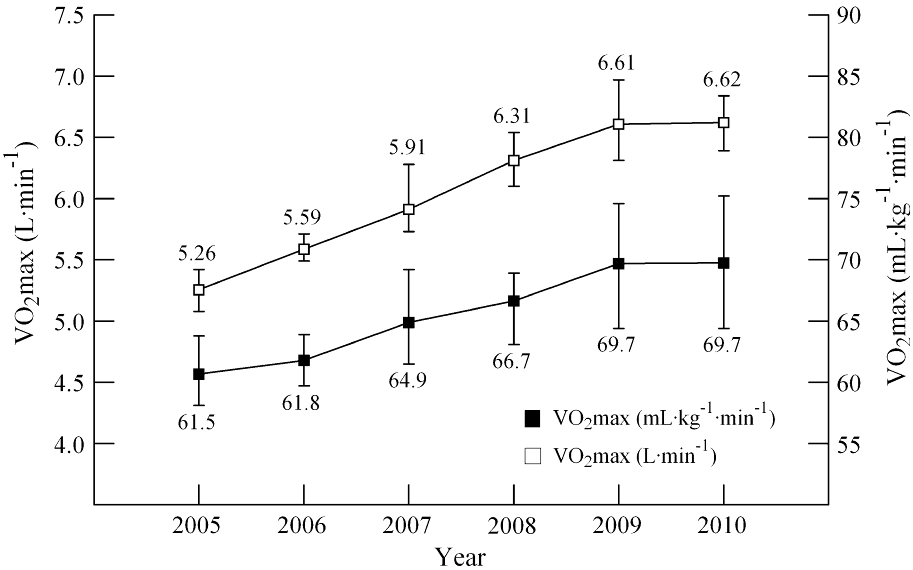

Fig. 1 Improvement in maximal oxygen uptake across time in four world-class rowers. *Error bars* represent minimum and maximum values and means are also shown as numerical values

2009). A 2004 Olympic champion (event not specified) recorded ~6.8 L min^{-1} (Godfrey et al. 2005); however, the rower was tested during the peak competition period, 8 weeks prior to the Olympics. Power at $\dot{V}O_{2max}$ (i.e., maximal aerobic power, expressed in Watts) in the monitored group of rowers also indicated a steady improvement of +20% between 2005 and 2010, amounting to a crew average of 481 W in 2010 (Table 1). As mentioned in "Introduction" section, both $\dot{V}O_{2max}$ in L min^{-1} and power corresponding to $\dot{V}O_{2max}$ are important parameters in monitoring rowers' training and performance as they frequently emerged as strong correlates and/or important predictors of 2000 m rowing ergometer performance (Maestu et al. 2005). It is interesting to note that, while $\dot{V}O_{2max}$ values exhibited no change over the last 2 years of assessment, the power at $\dot{V}O_{2max}$ over the same period increased from 459 to 481 W (+5%). This observation may indicate an improved technical efficiency in maturing rowers when exercising at very high work rates. Finally, it should be added that the maximal values obtained in 2010 were 235 (230–242) L min^{-1} and 35.2 (32.9–36.7) mL beat^{-1} for minute ventilation and oxygen pulse, respectively. These values provide further evidence regarding the well-documented extraordinary ventilation capacities and aerobic capabilities in top-caliber rowers.

Of the submaximal measures, there was a marked increase of +23% in power output corresponding to AT over the 2005–2009 period. In the last year of the study (2009–2010), a slight 2% reduction in this parameter was noted (Table 1). This slight decrease, along with stabilization in $\dot{V}O_{2max}$ over the same time period, may partly explain the stagnation in rowing ergometer performance times between 2009 and 2010 (see next paragraph). Note that $\dot{V}O_{2max}$ at AT increased continuously over the 6-year period, and the rate of its increase approximately parallels that of $\dot{V}O_{2max}$. Subsequently, $\dot{V}O_{2max}$ at AT expressed as a percentage of $\dot{V}O_{2max}$ remained relatively constant throughout the monitored period, i.e., between 82 and 85%.

Table 1 Changes in physical, physiological, and performance measures in four world-class rowers across time

	2005	2006	2007	2008	2009	2010
Mean age (years)	16.3	17.2	18.2	19.2	20.2	21.1
Stature (cm)	186 (185–188)	187 (185–188)	187 (185–189)	188 (186–189)	188 (186–189)	188 (186–190)
Body mass (kg)	87 (85–90)	90 (88–93)	91 (88–96)	95 (91–100)	96 (93–102)	95 (91–101)
Body fat (%)	13.4 (11.8–14.5)	12.0 (9.8—13.9)	11.2 (8.2–13.5)	10.2 (9.0–12.6)	9.9 (7.0–11.6)	9.4 (6.6–12.3)
Fat–free mass (kg)	75 (73–77)	80 (77–81)	81 (78–83)	85 (83–87)	87 (84–90)	86 (85–89)
Power at $\dot{V}O_{2max}$ (W)	400 (388–413)	431 (413–450)	431 (413–450)	456 (425–488)	459 (425–488)	481 (475–488)
Power at AT[a] (W)	297 (288–313)	338 (313–350)	338 (325–350)	353 (338–375)	366 (350–388)	359 (350–388)
$\dot{V}O_2$ at AT[a] (% of $\dot{V}O_{2max}$)	85 (83–88)	83 (80–86)	85 (83–87)	82 (80–83)	85 (83–87)	85 (81–89)

Data are presented as mean values (minimum value − maximum value)

[a] Anaerobic threshold

These values correspond to an earlier report on highly trained rowers by Bunc et al. (1987).

A 6-year improvement of +7% is evident both for 2000 and 6000 m average rowing ergometer performance times (Fig. 2). A curvilinear regression provided the best representation for a description of improvement in performance times over the monitored period ($R^2 = 0.984$, $P < 0.001$ and $R^2 = 0.989$, $P < 0.001$ for 2000 and 6000 m performance times, respectively). Rowing ergometer performance times are considered valuable indicators of a rower's sport-specific physical fitness, and 2000 m ergometer times have recently exhibited moderate to strong correlations with 2007 World Championship rankings at both junior (Mikulic et al. 2009a) and open class (Mikulic et al. 2009b) levels. A close inspection of 2000 m times indicated that four studied rowers were on average ~15-s faster in 2006 as junior rowers, and ~8-s faster in 2010 as open class rowers than the mean 2000 m ergometer performance time for all rowers competing in sculling events in 2007 World Junior Rowing Championships and World Rowing Championships, respectively. The relative improvements in ergometer performance declined almost continuously over the monitored period, with annual improvements (from 2005 to 2010) of +2.6%, +2.0%, +1.6%, +0.5%, and +0.3% for 6000 m time, and +2.5, +2.3%, +1.3%, +1.2%, and −0.3% for 2000 m time. As observed for $\dot{V}O_{2max}$, the stabilization of ergometer performance seems to be evident from 2009 onwards, an assumption based on very slight changes in performance times (i.e., ±0.3%) between 2009 and 2010. Of course, further annual assessments are necessary to verify the assumption that ergometer performance is stabilizing.

Finally, the rowers' training characteristics merit a brief discussion. Unfortunately, reliable details on the training of all crew members were available only for the final 2 years of the study (i.e., 2009 and 2010), when rowers spent >90% of their on-water training sessions together in the quadruple-sculls. During the off-water training periods of the 2009 and 2010 seasons, which typically stretched from mid-November to mid-February, the rowers trained primarily in their respective clubs, yet followed very similar training regimens. A close examination of training logs indicates that the average training characteristics observed in 2009 and 2010 were similar. The main difference was that, in 2010, because the 2010 World Rowing Championships were held unusually late in the rowing season (i.e., in early November), a considerably greater on-water distance was covered during September and October. On average, during 2009 and 2010 the training for all rowers consisted of 11.1 sessions per week of which 1.5 were land-based endurance training sessions in the form of running, hiking, cycling or cross-country skiing, 2.4 were weight room sessions, and 7.2 were rowing sessions. These rowing sessions consisted, on average over 2009 and 2010, of on-water rowing (83%), ergometer rowing (15%), and tank rowing (2%). The general training data for 2009 and 2010 are depicted in Fig. 3. The total distance covered on-water (averaged across rowers), including warm-up and cool-down rowing exercises, was 116 km week^{-1} in 2009 (6050 km per year) and 124 km week^{-1} in 2010 (6460 km per year). Collectively, although slightly higher in terms of the number of weekly training sessions, the presented values largely collaborate those reported by Lacour et al. (2009) in their description of the training volume and training characteristics of contemporary world champion rowers.

To sum up, this 6-year follow-up study of a world-class crew indicated that physical and physiological adaptations

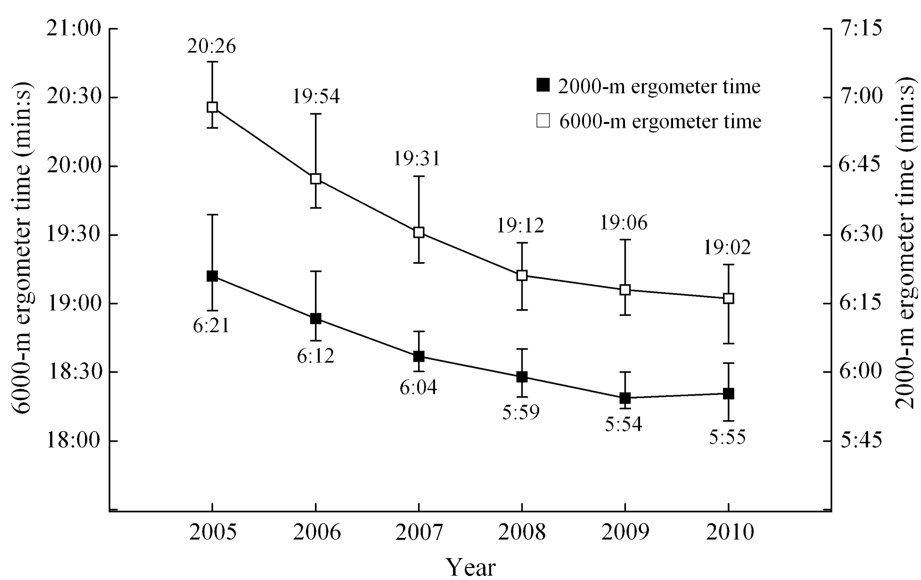

Fig. 2 Improvement in 2000 and 6000 m rowing ergometer performance times across time in four world-class rowers. *Error bars* represent minimum and maximum values and means are also shown as numerical values

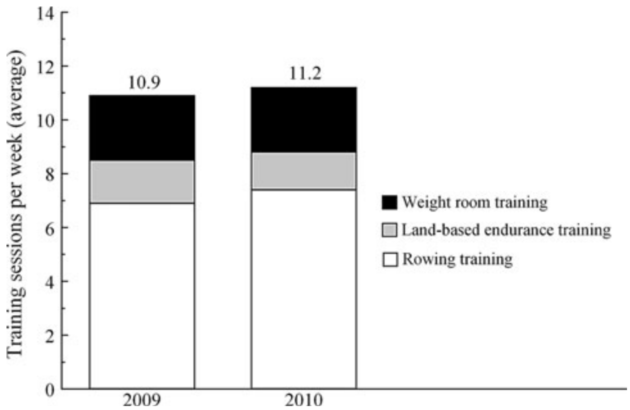

Fig. 3 Average weekly number and structure of training sessions in four world-class rowers for the last 2 years of assessment. Note that rowing training sessions encompassed on-water, ergometer, and tank rowing in the following respective percentages: 80, 18, and 2% in 2009 and 85, 14, and 1% in 2010

to accommodate long-term training appear to slow down considerably at about 20 years of age, subsequently causing rowing ergometer performance times to plateau. Although additional annual monitoring is required to confirm these findings, it appears likely that from about 20–21 years of age, an athlete's rowing training maintains a constant level of specific physiological and performance features, with substantial improvements seeming unlikely. Note that since the rowers were 15–16 years of age at the commencement of the study, the effects of training cannot be separated cleanly from those of the last stages of growth. Finally, the development of athletes from maturation to top-performance level has been previously presented in the literature; however, such information regarding the world-class athletes (e.g., Olympic and world champions) remains a largely speculative issue because of the finite nature of the population and due to limited access to such athletes. Hence, the findings presented here may contribute to the body of knowledge on athletes representing the true elites of their respective sports.

Conflict of interest There is no conflict of interest related to this work.

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