DISSERTATIONES KINESIOLOGIAE UNIVERSITATIS TARTUENSIS

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EVELIN LÄTT

Selected anthropometrical, physiological and biomechanical parameters as predictors of swimming performance in young swimmers

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CONTENTS

ABBREVIATIONS

BMC	bone mineral content
BMD	bone mineral density
BMI	body mass index
Body fat%	body fat percent
Cs	energy cost
DXA	dual-energy x-ray absorptiometry
E_{tot}	maximal total energy expenditure corrected for body mass
FFM	fat free mass
FM	body fat mass
SI	stroke index
SL	stroke length
SR	stroke rate
v	swimming velocity
VO_{2peak}	peak oxygen consumption
ΔLa	net increase of blood lactate

LIST OF ORIGINAL PUBLICATIONS

I **Jürimäe, J., Haljaste, K., Cicchella, A., Lätt, E., Purge, P., Leppik, A., Jürimäe, T.** Analysis of swimming perfromance from physical, physiological, and biomechanical parameters in young swimmers. *Pediatric Exercise Science*, 2007; 19: 70–82.

II **Lätt, E., Jürimäe, J., Haljaste, K., Cicchella, A., Purge, P., Jürimäe, T.** Physical development and swimming performance during biological maturation in young female swimmers. *Collegium Antropologicum*, 2009; 1: 117–122.

III **Lätt, E., Jürimäe, J., Haljaste, K., Cicchella, A., Purge, P., Jürimäe,T.** Longitudinal development of physical and performance parameters during biological maturation of young male swimmers. *Perceptual and Motor Skills*, 2009; 108: 297–307.

Paper I, Evelin Lätt had primary responsibility for protocol development, subjects' enrollment, performing measurement, data analysis and written the preliminary version of the article.

Papers II and III, Evelin Lätt had primary responsibility for protocol development, subjects' enrollment and performing measurement, data analysis, and writing the manuscripts.

1. INTRODUCTION

The relationships among human somatic traits, physical capacity, and performance in athletes at various ages have been a source of interest for many scientists. For example, several investigations have studied the anthropometric characteristics of successful swimmers (Grimston & Hay, 1986; Mazza et al. 1993; Siders et al. 1993; Sprague, 1976), whereas a number of studies have examined the relationship between these characteristics and the swimming performance (Grimston & Hay, 1986; Klentrou & Montpetit, 1991, Siders et al. 1993; Sprague, 1976). Swimming performance has also been related to different biomechanical parameters (Poujade et al., 2002; Tsekouras et al., 2005; Zamparo et al., 2000, 2005a). Specifically, competitive swimming is a cyclic sport activity performed with the aim of covering given distance as fast as possible (Barbosa et al., 2008) to maximize metabolic power of the athlete and the economy of locomotion. Hence it is important to assess the individual economy of swimming and to understand the factors that determine swimming performance (Zamparo et al., 2000). In swimming, the performance is influenced by the capacity of generating propelling power and minimizing the resistance to advance in the liquid environment (Schneider & Meyer, 2005). In any swimming event, maximal performance in swimming is dependent on a number of factors, including body size, stroke efficacy and also on the amount of metabolic energy spent in transporting the body mass of the athlete over the unit of swimming distance (Zamparo et al., 2005a). It has been reported that Cs varies largely from one swimmer to another, mainly depending on the specific anthropometrical (Chatard et al., 1985) and biomechanical (Montpetit et al., 1988) characteristics of the athlete. Metabolic energy has been assessed from the ratio of oxygen consumption (VO_2) to the corresponding swimming speed in adult athletes (Zamparo et al., 2005a). Oxygen-consumption values measured during recovery have been used to extrapolate backward to determine VO_{2peak} during maximal swimming and this method of determining VO_{2peak} has been reported to be valid in adult swimmers (Costill et al., 1985). The use of this methodology offers a specific in-water assessment of the VO_2 during swimming taking into account different anthropometrical and biomechanical parameters of the young swimmer.

Swimmers usually start serious training before the onset of puberty and achieve international competitive level at a relatively early age. Performance in swimming has been related to different anthropometrical, physiological and biomechanical parameters in children (Avlonitou, 1994; Damsgaard et al., 2001; Kjendlie et al., 2004b; Poujade et al., 2002). However, longitudinal data on the relations among physical traits, physiological capacity, and swimming performance for young swimmers are limited. This is despite the fact that metabolic capacities and skill acquisition are affected by growth and development (Bar-Or, 1994; Malina, 1994), suggesting that factors predicting swimming performance may vary for young swimmers during their physical maturing and may be different compared to adults. There could be also a wide variation in the biological age of children of the same chronological age, so it is necessary to consider the effects of growth and development when analyzing swimming performance in young swimmers. Furthermore, a complex interaction between different anthropometrical, biomechanical and physiological parameters that all affect swimming performance to some extent should be considered when evaluating the performance of the young swimmer. It appears that very few studies have investigated the importance of different anthropometrical, physiological and biomechanical parameters to determine swimming performance in children (Geladas et al. 2005; Poujade et al. 2002). To our knowledge no studies have been conducted to study longitudinally the effect of different anthropometrical, physiological and biomechanical parameters on swimming performance in complex in young male and female swimmers during their physical growth and maturation.

2. REVIEW OF THE LITERATURE

2.1. Biological maturation and anthropometrical parameters in young swimmers

Growth refers to increase in the size of the body (e.g. stature and body mass) or its parts, whereas biological maturation refers to the tempo and timing of progress towards the mature state (i.e. menarche and development of secondary sex characteristics). It has been suggested that differences in physique between young athletes probably reflect selection at relatively young age for the size demands of a specific sport, as elite adult athletes are known to have better anthropometrical and physiological characteristics specifically suited to their sport discipline (Bar-Or, 1975; Clarke, 1973). Individual differences in maturity status at a given age and in the timing of the adolescent growth spurt influence growth status and performance. Moreover, children who are successful in sport tend to differ, on average, in maturity status and rate compared with the general population (Beunen & Malina, 2008). Young athletes who begin to train seriously have pronounced functional advantages, but this finding may actually be related to other research showing that young athletes who regularly train in different sport disciplines, in general, have early sexual maturation (Malina, 1994). In other words, the athletes who begin training at relatively young age and experience success may actually do so because they are more physiologically mature than their chronologically age matched peers (Baxter-Jones & Maffulli, 2003). The range of variability between individuals of the same chronological age in somatic and biological growth is large and especially accentuated around the adolescent growth spurt (Iuliano-Burns et al., 2001; Marshall & Tanner, 1970, Tanner, 1978). However, growth in children is not a regular process, and different changes occur in the proportions of different body segments (Baxter-Jones & Maffulli, 2003).

Several investigations have studied the anthropometric characteristics of successful adult swimmers (Grimston & Hay, 1986; Mazza et al., 1993; Siders et al., 1993; Sprague, 1976), whereas a number of studies have examined the relationship between these characteristics and the swimming performance (Grimston & Hay, 1986; Klentrou & Montpetit, 1991, Siders et al., 1993; Sprague, 1976). In dividing swimming techniques according to style at sprint and long-distances, specific somatic properties must also or even above all, be taken into consideration. These somatic properties include first of all total body length, arm span and fat free mass. These somatic attributes are largely inherited and together with anaerobic capacity potential determine swimming technique to the highest degree (Avlonitou et al., 1997; Carter & Heath, 1990; Grimston & Hay, 1986; Seifert et al., 2007). An association between body form and stroke length has been found and it has also been concluded that parameters such as body height, and the cross sectional and surface area of the body may be important to success in swimming (Geladas et al. 2005).

Participating in a competitive sport at a young age has been associated with a specific body composition and body proportions (Claessens et al., 1991, Damsgaard et al., 2001). The processes of growth and maturation are related, and both exert an influence on the physical performance of the athlete (Beunen and Malina, 2008). It has been demonstrated that biological age is a better predictor of performance than chronological age in various sport disciplines (Beunen, 1989; Beunen & Malina, 2008; Khosla, 1983). The advantage of advanced sexual maturity for selection into certain sports is also highlighted by the observation that in some sports athletes who are born at the beginning of the selection year had a distinct advantage of being selected as having talent over those born late in the year (Brewer et al., 1995). Results have suggested that in sports where large physiques are necessary for competitive success (e.g. swimming), young athletes tend to be towards advanced sexual maturation at their chronological age (Baxter-Jones & Helms, 1996). Accordingly, it is important to consider also biological maturation when evaluating different performance-related parameters in a specific sport discipline including swimming.

To be successful at the international level of swimming competition, it is believed that intensive training must begin before puberty (Erlandson et al., 2008). Swimming is a sport where the entry for serious training starts from very young age while the children's body is under fast development. Young competitive female swimmers are taller and have higher fat free mass and lower percent body fat than their non-athletic counterparts (Avlonitou, 1994). In addition, Stager et al. (1984) studied a large group of 12–17 year old female swimmers and found that the faster swimmers had greater fat free mass, but did not differ in body fatness from slower swimmers. Swimmers seemed to be taller and more advanced in their puberty compared with peers (Baxter-Jones & Helms, 1996; Damsgaard et al., 2001; Theintz et al., 1993). It is considered that athletes may be selected into a certain sport or even event within the same sport on the basis of how closely their anthropometric profile represents the prototype for that sport or event. Until now, there have been very few studies conducted to examine different anthropometrical parameters in various age groups in swimming. Furthermore, there is not enough knowledge about how different anthropometrical parameters may affect swimming performance in young swimmers, especially during their biological maturation. For example Geladas et al. (2005) found that freestyle swimming performance was associated with certain anthropometrical and physical capacity variables in young swimmers (12–14 year old). Saavedra et al. (2010) results indicate that age and specific fitness in young swimmers (11–14 year old), particularly those related with aerobic and speed endurance, are main predictors of performance and that anthropometrical and technical variables are less relevant, except for females, in which technical variables reach high levels of correlation with swimming performance even when controlling for age. Strzala et al. (2005) found that 400-m swimming performance is mainly affected by anaerobic capacity and less by anthropometrical parameters in adolescent (15–17 year old) swimmers. In conclusion, studies have been performed concerning swimming performance and anthropometrics cross-sectionally in young swimmers. However it is also important to study these parameters longitudinally during puberty, since there are rapid changes in anthropometrical parameters during puberty.

2.2. Physiological parameters that affect swimming performance in young swimmers

Front-crawl swimming is a sport discipline that is fundamentally different from both running and cycling. The lying body position used in swimming reduces blood hydrostatic pressure in the legs as compared with the upright position used in cycling and running (Demarie et al., 2001). This may involve a lower perfusion in the capillary bed of the working muscle, resulting in a reduction in both blood flow and oxygen transport (Holmer, 1972). The effects of training on maximal aerobic power (assessed as peak oxygen consumption; VO_{2peak}) during growth and development has been and continues to be a subject of interest for physiologists and sport scientists (Armstrong & Welsman, 1994; Cunningham et al., 1984; Kobayashi et al., 1978; Krahenbuhl et al., 1985).

A large number of young athletes (e.g. swimmers) train for competitive sport before puberty, yet the understanding of their capabilities to benefit from serious endurance trainings is limited (Armstrong, 2000). Performance in endurance sports (running, swimming cycling, rowing, etc) improves steadily throughout childhood (Baxter-Jones et al., 1993). Few studies have investigated the relation between VO_{2peak} and sexual maturity (Armstrong & Welsman, 2001; Baxter-Jones et al., 1993; Mirwald & Bailey, 1986). With a log-linear scaling method, VO_{2peak} increased throughout childhood to puberty in both boys and girls, but there was a progressive divergence in values in favour of boys (Armstrong & Welsman, 2001). After puberty, VO_{2peak} continues to increase in boys but it levels off in girls as they approach adulthood (Armstrong & Welsman, 1994), probably a consequence of the increase in subcutaneous fat in (Kemper, 1985). Endurance capabilities of children improve as they become older and increase in body size (Baxter-Jones & Maffulli, 2003). This improvement differs slightly in boys and girls, as girls increase their capabilities in a similar way to boys, but with less magnitude (Armstrong & Welsman, 1994; Mirwald & Bailey, 1986). Rowland & Boyajian (1995) have stated that there is a limited evidence to suggest that training during pre-pubertal years increases VO_{2peak} beyond the increases attributed to growth. Bar-Or (1983) has concluded that VO_{2peak} responds positively to endurance training in pre-pubertal children. Two hypotheses have been presented to explain the contentious relationship of maturation to children's aerobic power (Armstrong & Welsman, 1994; Baxter-Jones et al., 1993), namely that a maturational threshold exists before which children are unable to elicit physiological changes in response to training, and/or that adolescence is a critical period during which children are particularly susceptible to aerobic training. It has been demonstrated that young swimmers present higher values for VO_{2peak} at all pubertal stages (Baxter-Jones et al., 1993) when compared to a normal untrained population (Baxter-Jones & Helms, 1996).

It is advantageous to measure VO_{2peak} at sport-specific conditions, which allows evaluating the athlete during swimming. Costill et al. (1985) proposed a method to evaluate VO_{2peak} in adult swimmers at sport-specific conditions. Specifically, VO_{2peak} values measured during recovery after maximal 400-m front-crawl swimming have been used to extrapolate backward to determine the VO_{2peak} during maximal swimming bout (Costill et al. 1985). This method of determining VO_{2peak} during maximal swimming has been reported to be valid in adult swimmers, offering a specific in-water assessment of the oxygen consumption during swimming (Costill et al., 1985, Lavoie et al., 1983; Montpetit et al., 1981). It has been reported that the VO_{2peak} of front-crawl swimming increases exponentially as a function of swimming velocity (Capelli et al., 1998; Pendergast et al., 1977; Termin & Pendergast, 2000; Unnithan et al., 2009; Zamparo et al., 1996). Using this methodology to asses VO_{2peak} enables the swimmer to perform swimming without restrictions and does not intervene with the swimming technique of the athlete and using this parameter allow to calculate Cs in sport specific condition.

Maximal performance in swimming as well as in other forms of human locomotion depends on the amount of metabolic energy spent in transporting the body mass of the athlete and on the economy of locomotion (Capelli et al., 1998; Kjendlie et al., 2004a,b,c; Zamparo et al., 2000). Many studies have been performed on the energy cost (Cs) of swimming in trained or experienced adult swimmers (Barbosa et al., 2008; Capelli et al., 1998; Chatard et al., 1985, 1990, 1991; Chatard & Wilson, 2008; Costill et al., 1985; Pendergast et al., 1977; Zamparo et al., 2005a), few have investigated the swimming economy in children (Kjendlie et al., 2004a; Poujade et al., 2002; Zamparo et al., 2000, 2008). It has been reported that Cs varies largely from one swimmer to another, mainly depending on the specific anthropometrical (Chatard et al., 1985) and biomechanical (Montpetit et al., 1988) characteristics of the athlete. It might be expected that the Cs would change as young swimmer develops from a child into adulthood, as a consequence of growth, due to the changing drag and buoyancy and the improvement of the swimming technique (Kjendlie et al., 2004a). The technical ability of the swimmer and the overall efficiency strongly affect the Cs at a given swimming speed (Barbosa et al., 2008). Cs increases as a function of velocity (Capelli et al., 1998; di Prampero, 1986; Poujade et al., 2002; Zamparo et al., 2000) and has usually been assessed from the ratio of oxygen consumption and the corresponding velocity (v) in swimmers (Capelli et al., 1998; Kjendlie et al., 2004a,b; Zamparo et al., 2000, 2011). A decrease in the energy cost of swimming by improved biomechanics and/or an increase in metabolic power through effective training should act to improve competitive swimming performance (Termin & Pendergast, 2000). At variance with other sport activities (e.g. cycling) where minimal differences in efficiency are observed among subjects with different technical abilities, skill greatly influenced the energy cost of swimming (Holmer, 1974): the lower the skill level, the higher the Cs for a given swimming speed and stroke. Several studies have only analyzed the aerobic contribution to the swimming economy (Chatard et al., 1990; Holmer, 1974; Van Handel et al., 1988). In few studies, Cs has also been estimated at maximal speed wherein the anaerobic-energy contribution had to be considered in the calculation of the overall energy balance of the exercise (Camus & Thys, 1991; Capelli et al., 1998; Ogita et al., 1996; Zamparo et al., 2000). While measured oxygen consumption has been used to assess the aerobic energy contribution, net increase in blood lactate concentration after the swimming trial has been used to assess the anaerobic energy contribution in the calculation of Cs (Zamparo et al., 2005a, 2011).

As indicated by several studies in the literature, women have lower energy cost than men during swimming (Chatard et al., 1990, 1991; Montpetit et a., 1983, 1988; Pendergast et al., 1977; Zamparo et al., 2000, 2011) and their higher economy is traditionally attributed to a smaller hydrodynamic resistance due to their smaller size, larger percentage of body fat and more horizontal position in comparison to male swimmers. Significant relationships were found between the Cs and the swimming velocity in boys and adult swimmers (Chatard et al., 1990, 1991; Poujade et al., 2002). Kjendlie et al. (2004a) reported significantly lower energy cost in children (12-year-old boys) than in adults (21-year-old males) at comparable swimming speed, thus confirming the results obtained by Ratel & Poujade (2009) in a group of 12- year-old boys and 18–22 year old men. However, to our best knowledge, no studies have been performed, where sport-specific VO_{2peak} during maximal swimming has used to assess Cs in young swimmers. There is also limited information available about the swimming economy of children (Kjendlie et al., 2004a).

2.3. Biomechanical parameters that affect swimming performance in young swimmers

The understanding of the behavior of stroke mechanics and its relationship to swimming velocity (v) is one of the major points of interests in biomechanical research in swimming (Alberty et al., 2004; Dekerle et al., 2005; Hay, 1987; Keskinen & Komi, 1993). For example, if the starts and turns are ignored, the time required to cover a given distance can be expressed as a velocity (Termin & Pendergast, 2000). In this sense, mean swimming velocity is the best measure for swimming performance. Despite the importance of the physiological determinants of swimming, it is a sport in which technical skills assume fundamental importance, suggesting a combined evaluation of stroking and physiological parameters (Anderson et al., 2006; Psycharakis et al., 2008). Mean swimming velocity is a result of successive arm and leg actions during stroking, and consequently it can be described by its mechanical elements: stroke length and stroke rate (Barbosa et al., 2008). Increases or decreases in swimming velocity are due to a combined increase or decrease in stroke rate (SR) and stroke length (SL) (Barbosa et al., 2008; Craig et al., 1985; Dekerle et al., 2005; Hay, 1987; Keskinen and Komi, 1993, Kjendlie et al., 2006; Toussaint et al., 2006).

Accordingly, most of the biomechanical studies that have been carried out in swimmers have concerned the relationship between SR (cycles/min), SL (m/cycle) and swimming performance (Capelli et al., 1995; Huot-Marchand et al., 2005; Kjendlie et al., 2004c; Poujade et al., 2002) and are often used by coaches in the evaluation of training process (Maglischo, 2003). In case of various swimmers, depending on training status and distance covered, these parameters reach different levels. Mainly in youth groups, depending on training character, their impact on front-crawl swimming speed may change (Strzala & Tyka, 2009). Coaches opinions and some researchers reports prove that front-crawl swimming results are most strongly correlated with SL (Arellano et al., 1994; Cardelli et al., 2000; Costill et al., 1992; Kennedy et al., 1990). Studies by Keskinen et al. (1989) and Wakayoshi et al. (1995) have demonstrated that SL appears to be a major factor determining maximal or submaximal performance in swimming. Several authors have reported that similar swimming performances are characterized by greater variability in SL than in SR (Changalur & Brown, 1992; Craig & Pendergast, 1979; Kennedy et a., 1990; Keskinen & Komi, 1993; Pelayo et a., 1994). Accordingly, the proper SL should be instructed first to young swimmers, because it is tightly bound to the development of advanced swimming technique, hydrodynamic excellence and higher swimming efficiency. However, it has also been shown that there is a characteristic relationship between SR and swimming velocity (Chollet et al., 1997; Craig et al., 1985; Craig & Pendergast, 1979). These studies have demonstrated that faster swimmers swim with a greater distance per stroke at both slow and fast speed, have a greater ability to shorten their stroke, and have a higher maximal stroke rate. In addition, it has been found that elite swimmers swim shorter distance per stroke and slower stroke rates during all competitive events than they theoretically could, based on their individual stroke frequency-velocity relationship (Craig et al., 1985).

Stroke mechanics is considered to reach an optimal balance between SR and SL (Chollet et al., 1996; Pelayo et al., 1996) when v values are at their highest level with a relatively low energy cost (Barbosa et al., 2008). It has been shown that increases in maximal v from the age of about 11 are related to increased SL, while SR at maximal v does not increase with age (Kjendlie et al., 2004c). According to the literature, at a given v, energy cost significantly increases with increasing SR (Barbosa et al., 2005; Klentrou & Montpetit, 1992; Smith et al., 1988; Wakayoshi et al., 1995; Zamparo et al., 2005b). Less consistent is the decrease of energy cost with increasing SL (Barbosa et al., 2005; Costill et al., 1985; Pendergast et al., 2003; Smith et al., 1988; Termin & Pebdergast, 2000; Wakayoshi et al., 1996; Zamparo et al., 2005b).

Another parameter of swimming technique used is the stroke index (SI; m^2/s/cycles), considered as a valid indicator for swimming efficiency in adults (Costill et al., 1985) and also in children (Barbosa et al., 2010). SI has been calculated by multiplying the swimming speed by the SL (Barbosa et a., 2010; Costill et al., 1985; Seifert et al., 2010). SI is an indicator of swimming economy since it describes the ability to move at a given velocity with the fewest number of strokes and high stroke index values are strongly associated with low C_s (Costill et al., 1985). In this sense, SI can also be used as an overall estimation of swimming efficiency. To our best knowledge only Barbosa et al., (2010) recently examined SI influence in swimming performance in young swimmers.

Young swimmers learn to control the structure and efficiency of the movement while they grow up and mature in the process of a 5–7-year training program. During that time they pass through pre-pubertal and pubertal stages of ontogenesis when rapid physical growth and motor development take place. Significant changes in body build, motor abilities and fitness may be reflected in the "macro" structure and efficiency of sport techniques. It has to be taken into account that anthropometric parameters among other factors that may influence the relationship between SR and SL and affect swimming speed are related to stroke rate and, more importantly, stroke length in adults (Grimston & Hay, 1986; Pelayo et al., 1996) and also in children (Geladas et al., 2005; Poujade et al., 2002). This clearly demonstrates that anthropometric and biomechanical parameters are related and should be considered during growth and biological maturation in young swimmers. Furthermore, it has been suggested that changes in different swimming technique variables such as SL could also be related to simultaneous changes in metabolic variables such as blood lactate concentration after maximal swimming (Keskinen & Komi, 1993; Wakayoshi et al., 1996; Weiss et al., 1988). Thus, evaluating specific biomechanical parameters in swimming, different anthropometric and metabolic parameters should also be taken into account. Furthermore, during biological maturation and also further excellence in swimming in adult swimmers, different anthropometric and metabolic parameters may influence swimming technique to a certain extent. Knowledge of the age particulars and year-by-year dynamics of technical characteristics may allow us to control and correct the process of technical preparation in young swimmers (Vorontsov & Binevsky, 2002). In summary, it may be suggested that technical preparation of young swimmers is closely related to specific anthropometric parameters and these anthropometric parameters should be taken into account when teaching swimming technique for young swimmers.

2.4. Summary

Swimmers start to train seriously at relatively young age, usually before puberty. However, at present, very few studies have investigated the importance of anthropometrical, physiological, and biomechanical parameters to determine swimming performance in children. For example, Poujade et al. (2002) and Zamparo et al. (2000) studied children older than 12 years of age and determined the Cs during maximal 400-m front-crawl swimming. Recent study by Barbosa et al. (2010) developed a model based on biomechanical and energetic variables to predict 200-m front-crawl swimming performance in 12-year old boys. However, it was concluded that the model should be expanded, including more variables to increase the prediction level and show deeper understanding of the swimming performance in young swimmers during biological maturation (Barbosa et al. 2010). For example, it has to be taken into account that changes from prepuberty to puberty are important and include changes in different anthropometrical, physiological, and biomechanical parameters (Poujade et al., 2002). However, these anthropometrical, physiological and biomechanical parameters may affect differently the development of swimming performance during biological maturation and further swimming excellence. While some parameters may be more important at the beginning of serious swimming trainings, other parameters may affect more swimming performance at later stages of biological maturation. These different parameters should be studied in complex to better understand the development of swimming performance in young swimmers. However, to our best knowledge, no studies have longitudinally investigated the development of swimming performance in young male and female swimmers during their biological maturation taking into account different anthropometrical, physiological and biomechanical parameters.

3. AIM AND THE PURPOSES OF THE STUDY

The general aim of the present study was to investigate the impact of specific physiological, biomechanical and anthropometrical parameters on the development of swimming performance during biological maturation in young male and female swimmers.

Specific aims of the present study were to:

1. compare the indirect in-water measurement of peak oxygen consumption with laboratory-based measurement of peak oxygen consumption and calculate the metabolic energy cost of swimming;
2. investigate the development of specific physiological, biomechanical and anthropometrical parameters of young male swimmers during their biological maturation;
3. investigate the development of specific physiological, biomechanical and anthropometrical parameters of young female swimmers during their biological maturation;
4. find which group of parameters (i.e., anthropometrical, physiological or biomechanical) characterize best improvement in swimming performance of young male swimmers during their biological maturation;
5. find which group of parameters (i.e., anthropometrical, physiological or biomechanical) characterize best improvement in swimming performance of young female swimmers during their biological maturation.

4. METHODS

4.1. Participants

In total, 29 male (age 13.0±1.8 yrs, height 163.3±11.9 cm, body mass 51.6±13 kg) and 26 female (age 12.7±2.2 yrs, height 160.9±9.3 cm, body mass 50.3±9.2 kg) swimmers participated in the study. At the beginning of the study, all males and females had a training background of 3.0±1.1 and 3.7±1.8 years, respectively and had been training for 8.4±1.7 and 6.2±1.9 hrs/week for at least the last 2 years, respectively. During the study period the participants continued to train in accordance with their scheduled training plan. Their training volume increased for about 7% during two years. Their training consisted of approximately 75% in the pool and 25% dryland training, of which not more than 30% was strength training and the rest other forms of exercises (stretching, ball games, running etc.). The training plan of the subjects was kept constant according to what has been scheduled by the coaches. The analysis of the study was not revealed to coaches during the study period, therefore coaches were not able to change the training plan for the special improvement of these capacities that were the best predictors of the performance. All children and parents were precisely informed about the purposes and contents of the study and written informed consent was obtained from the parents before participation. This study was approved by the Medical Ethics Committee of the University of Tartu.

4.2. Study design

The study was initiated in September 2005 (Time 1) and all subjects participated in three testing occasions during two years (Times 2 and 3). Every testing occasion included three testing sessions. During the first session main anthropometrical parameters and biological age were measured. In addition, VO_{2peak} on cycle-ergometer was also measured during the first testing session at Time 1. The second measurement session consisted of maximal 400-m front-crawl swimming test in the swimming pool. During the third measurement session, the body composition parameters were measured using dual-energy X-ray absorptiometry (DXA). The first and second measurement sessions were separated by at least 48 hrs, and the third measurement session depended on the participants' schedules and DXA availability at the hospital, but for no longer than one week away.

4.3. Biological age, anthropometrical parameters and body composition

The biological age of the participants was assessed according to the self-assessment using an illustrated questionnaire of the pubertal stages according to the Tanner classification method (Tanner, 1962). The pubertal development assessment according to Tanner method which uses the self-assessment of breasts and the pubic hair stage in girls and genitalia and pubic hair stage in boys, has been previously validated (Duke et al., 1980; Saito, 1984). The participants were given photographs, figures and descriptions, and asked to choose the one that most accurately reflected their appearance. In case of discrepancies between the two variables (breast development and pubic hair stage in girls and genitalia development and pubic hair stage in boys), a greater emphasis for the determination of the Tanner stage was placed on the degree of the breast or genitalia development in girls and boys, respectively (Duke et al., 1980).

The body height was measured to the nearest 0.1 cm using Martin metal anthropometer according to the standard technique and the body mass was measured with minimal clothing with medical balance scale (A&D Instruments, UK) in kg (±0.05 kg). Body mass index (BMI) was calculated as body mass (kg) divided by height squared (m^2) Arm span was measured to the nearest 0.1 cm according to the standard recommendations (Norton & Olds, 1996).

Whole-body fat mass (FM), fat free mass (FFM), body fat percent (body fat%) and bone mineral content (BMC) were measured using the DPX-IQ densitometer (Lunar Corp., Madison, WI, USA) equipped with software version 3.6. Participants were scanned in light clothing while lying flat on their backs with their arms at their sides. The fast-scan mode and standard participant positioning were used for total-body measurements, and participants were analyzed with the use of the extended-analysis position. Bone mineral density (BMD) was determined as the total body BMD and at the site of the posterior-anterior spine. Coefficients of variations for measured FM, FFM, BMC and BMD values were less than 2%.

4.4. Peak oxygen consumption

Peak oxygen consumption (VO_{2peak}) was directly measured on an electronically braked cycle ergometer (Tunturi T8, Finland). A standardized 2-min warm-up at 60 W was completed prior to testing. Participants performed an initial work rate of 80 W with an increments of 20 W every 2-min in order to attain a test approximately 8–10 min in duration. At the end of last work rate, participants were required to sprint as fast as possible for 1 min. Participants were actively encouraged to continue until voluntary exhaustion. Heart rate was recorded every 5 s during the test using a Sporttester Polar Vantage NV (Kempele, Finland). Gas exchange variables were measured throughout the test in a breath-bybreath mode and data were stored in 10 s intervals. During the test, participants breathed through a face mask. Oxygen consumption (VO_2) was continuously measured using a portable open-circuit system (MedGraphics $VO_2$00, St. Paul, MN, USA). The analyzer was calibrated with the gases of known concentration before the test. All data were processed by computer analysis using standard software.

4.5. Maximal 400-m swimming test

Maximal 400-m front-crawl swimming test was performed in a 25-m indoor swimming pool. Each swimmer performed 400-m swimming at a maximal evenly paced effort (Costill et al., 1985; Poujade et al., 2002). The swimmers started without diving from the starting block and did not perform regular turning motions at the end of the lane but instead resumed swimming immediately without gliding underwater after the turn (Kjendlie et al., 2004a; Zamparo et al., 2000). Capillary blood samples for the measurement of blood lactate concentration (La; mmol/l) were taken from the fingertip at the third, fifth and seventh minute after the trial (Baxter-Jones et al., 1995; Capelli et al., 1998; Zamparo et al., 2005a) and analyzed using an enzymatic photometric method (Lange Microanalyzer, Lange GMBH, Berlin, Germany). The net increase of blood lactate (ΔLa) was obtained by subtracting the pretrial value (equal to 1 mmol/l) from the peak value attained during the recovery phase (Kjendlie et al., 2004a; Zamparo et al., 2000).

The backward-extrapolation technique was used to evaluate VO_{2peak} during the 400-m front-crawl swimming bout (Costill et al., 1985; Tsekouras et al., 2005; Zamparo et al., 2000, 2005a). Each swimmer was instructed to exhale the last breath into a breathing mask as soon as it was fitted over his head (approximately 1–3 s after finishing) (Costill et al., 1985; Zamparo et al., 2000). Metabolic values of VO_2 were determined by a portable open-circuit system (MedGraphics $VO_2$00, St. Paul, MN, USA) during the first 20 s of the recovery at the end of the 400-m front-crawl swimming bout (Costill et al., 1985; Tsekouras et al., 2005; Zamparo et al., 2000, 2005a). Gas sensors and a ventilatory-flow transducer were calibrated using gases of known concentrations before each experimental run, following the procedure indicated by the manufacturer. To validate the indirect in-water measurement of $VO_{2peak,}$ the results were compared with the VO_{2peak} results obtained on a cycle-ergometer test.

During the maximal 400-m front-crawl swimming test, the energy cost of swimming and stroking parameters were assessed (Poujade et al., 2002; Zamparo et al., 2000). To exclude the influence of turning and start, the average swimming velocity (v; m/s) maintained by each swimmer during the trail was measured over 15 m within two points 5.0 m distance from each end of the pool ($v=D/t_{15}$, where D=15 m and t_{15}=time for the 15 m) (Poujade et al., 2002; Zamparo et al., 2005a). A video camera (Sony DCR-TRV 130E, Japan) was used to record the trials of each swimmer with a profile view from aside the pool. The camera was also measured the time over a distance of 15 m (Leblanc et al. 2005). The video recording covered at least five stroke cycles for each trial (Leblanc et al., 2005). Average stroke rate (SR; cycles/min) was the average number of strokes completed by the swimmers during the 15-m distance (Alberty et al., 2006; Leblanc et al., 2005; Poujade et al., 2002). Stroke length (SL; m/cycle) value was calculated as the ratio between average velocity and the corresponding SR (Alberty et a., 2006; Leblanc et al., 2005; Poujade et al., 2002). Finally, in an effort to gauge the economy of a swimmer's technique. a stroke index (SI; m^2/s/cycles) was calculated by multiplying the swimming velocity by SL (Costill et al., 1985).

The energy cost of swimming (C_s; kJ/m) was calculated by dividing the difference between measured VO_2 of the maximal 400-m front-crawl swimming test and VO_2 at rest, assumed to amount to 5 ml O_2/kg/min (Capelli et al., 1995), by the average swimming speed (di Prampero, 1986; Poujade et al. 2002; Zamparo et al., 2005a). The C_s was expressed in kilojoules per meter on the assumption that 1 l of O_2 consumed in the human body (at standard temperature and pressure) yields 20.9 kJ of metabolic energy (Capelli et al., 1995; Zamparo et al., 2005a). Anaerobic contribution to the overall energy expenditure was obtained from the energetic value of ΔLa, which was calculated on the basis of equivalent of 0.0689 kJ/kg/mM (di Prampero, 1986). Finally, the energetic value of ΔLa was divided by the overall distance covered and added to the aerobic-energy cost obtained, as already described, to yield the overall C_s (Zamparo et al., 2005a).

4.6. Statistical analysis

Data analysis was performed using SPSS 13 for Windows (Chicago, IL, USA). Standard statistical methods were used to calculate means and standard deviations (mean±SD). Evaluation of normality was performed with the Shapiro-Wilks statistical method. Regression analysis and limits of agreement between directly measured VO_{2peak} on a cycle- ergometer and indirectly measured VO_{2peak} were derived following the procedures recommended by Bland and Altman (1986). One way analysis of variance for repeated measurements was used to examine changes over time. Where appropriate, post hoc analysis was completed with Scheffe test to assess where significant differences existed. Multivariate linear regression analyses were performed to determine the potential associations of swimming performance with different variables of interest and to find which group of parameters (i.e., anthropometrical, physiological or biomechanical) characterize best the improvement in swimming performance. The interperiod Spearman correlation coefficients were also used as tracking coefficients (Beunen et al., 1992; Leppik et al., 2006). All time points were correlated with the baseline measure (Time 1) and additionally, between measurements at Times 2 and 3 (Leppik et al., 2006). Statistical significance was set at $p<0.05$.

5. RESULTS

5.1. Peak oxygen consumption and energy cost of swimming

To validate the indirect in-water measurement of VO_{2peak} in studied boys, the results were compared with the VO_{2peak} results obtained on a bicycle-ergometer test (bicycle: 2.86±0.74 l/min vs. in water: 3.20±1.0 l/min; adjusted R^2=0.713; $p<0.05$). Similarly, the indirect in-water measurement of VO_{2peak} (2.61±0.54 l/min) in studied girls was comparable to the VO_{2peak} (2.95±0.56 l/min) obtained on a cycle ergometer test (adjusted R^2=0.679; $p<0.05$). Figure 1 shows the results of the Bland-Altman analysis for indirect in-water and laboratory measurements of VO_{2peak} in boys (A) and girls (B). The agreement between directly measured VO_{2peak} on a bicycle ergometer and indirectly calculated VO_{2peak} after swimming was high for both groups of swimmers. The in-water measurement of VO_{2peak} together with the net increase in blood lactate (boys: 4.6±2.5 mmol/l; girls: 4.2±2.0 mmol/l) after the swimming distance allowed us to compute the energy cost of swimming during maximal 400-m front-crawl swimming. Cs values averaged 2.82±0.71 kJ/m and 1.55±0.46 kJ/m for boys and girls, respectively.

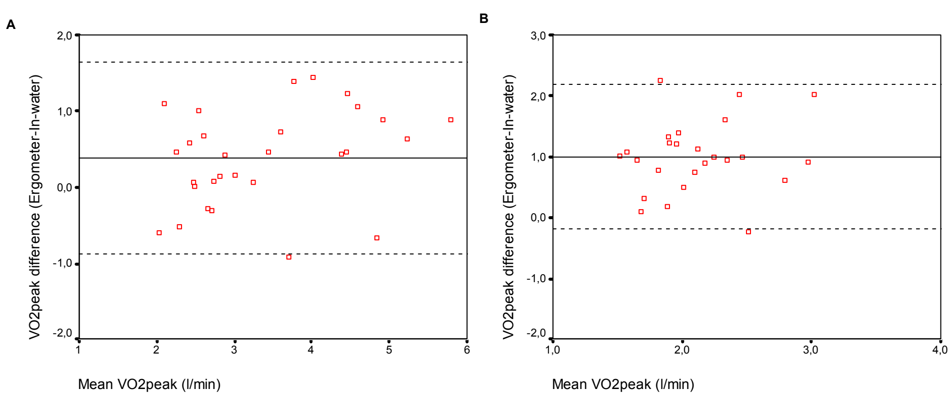

Figure 1. Relationship between in-water and ergometer measurements of peak oxygen consumption (VO_{2peak}) in male (A) and female (B) young swimmers

5.2. Development of physiological, biomechanical and anthropometrical parameters and swimming performance in young male swimmers

During the 2-year follow-up study period, age, height, body mass, BMI, FFM, BMC, spine BMD, arm span and physical maturity values significantly increased during each year ($p<0.05$) (Table 1). However, increases in FM and total BMD values between the second and third measurements, and the first and second measurements, were not significant ($p>0.05$). The percent body fat did not change significantly during the study period. Performance time, Cs and VO_{2peak} of the 400-m front-crawl swim improved significantly during each year (Table 2). Mean swimming v, SL, SR and SI for the swimming test were significantly improved only at the third measurement, while ΔLa was significantly increased after the first measurement and no changes occurred between the second and third measurement point.

Table 1. Mean (±SD) anthropometrical and body composition parameters in young male (n=29) swimmers over three measurement points

Variable	First measurement	Second measurement	Third measurement
Age (yrs)	13.0±1.8	14.0±1.8*	15.1±1.8*#
Height (cm)	163.3±11.9	169.6±9.8*	173.5±8.5*#
Body mass (kg)	51.6±13.0	57.2±12.2*	61.7±10.9*#
BMI (kg/m^2)	18.9±2.4	19.5±2.4*	20.4±2.3*#
Body fat%	12.1±5.3	12.1±5.4	11.8±4.3
FM (kg)	5.8±2.9	6.3±3.6*	6.7±2.8*
FFM (kg)	42.2±11.2	45.2±11.6*	47.9±10.3*#
BMC (kg)	2.2±0.7	2.3±0.8*	2.5±0.6*#
Total BMD (g/cm^2)	1.0±0.1	1.0±0.1	1.1±0.1*
Spine BMD (g/cm^2)	0.9±0.2	0.9±0.2*	1.0±0.2*#
Arm span (cm)	168.8±13.7	174.6±11.6*	177.7±10.4*#
Tanner stage	2.3±1.0 (1–4)	3.4±1.0* (2–5)	4.1±0.8*# (3–5)

BMI-body mass index, Body fat% – body fat percent, FM – body fat mass, FFM – fat free mass, BMC – bone mineral content, BMD – bone mineral density
* Significantly different from the first measurement; p<0.05.
# Significantly different from the second measurement; p<0.05.

Table 2. Mean (±SD) biomechanical and physiological parameters obtained from the maximal 400-m front crawl swimming in male (n=29) swimmers over three measurement points

Variable	First measurement	Second measurement	Third measurement
Time (s)	373.3±53.5	362.5±53.2*	351.5±50.4*#
v (m/s)	1.05±0.14	1.06±0.13	1.09±0.14*#
SL (m/cycle)	0.92±0.12	0.95±0.12	1.01±0.14*#
SR (cycle/min^1)	68.7±5.3	67.3±8.0	65.7±7.9*#
SI (m^2/s/cycles)	0.99±0.24	1.01±0.23	1.12±027*#
Cs (kJ/m)	2.82±0.71	3.07±0.64*	3.43±0.66*#
VO_{2peak} (l/min)	3.20±1.03	3.44±0.75*	3.94±0.76*#
ΔLa (mmol/l)	4.6±2.5	6.0±1.9*	6.0±2.3*

v – swimming velocity, SL – stroke length, SR – stroke rate, SI – stroke index, Cs – energy cost, VO_{2peak} – peak oxygen consumption, ΔLa – net increase of blood lactate
* Significantly different from the first measurement; p<0.05.
# Significantly different from the second measurement; p<0.05.

The stepwise regression analyses revealed that SI (R^2=0.898; p<0.05), arm span (R^2=0.454; p<0.05) and VO_{2peak} (R^2=0.358; p<0.05) were the best predictors of 400-m front-crawl swimming performance from the measured biomechanical, anthropometrical and physiological parameters at the first measurement time, respectively. At the second and third measurement points, SI (R^2>0.726; p<0.05) from the measured biomechanical parameters, height (R^2>0.299; p<0.05) from the measured anthropometrical values, and VO_{2peak} (R^2>0.223; p<0.05) from the measured physiological values were the best predictors of 400-m front-crawl swimming performance. According to the stepwise regression analyses, it appeared that biomechanical factors (R^2>0.726; p<0.05) characterised best the 400-m swimming performance in young swimmers, followed by anthropometrical (R^2>0.299; p<0.05) and physiological (R^2>0.223; p<0.05) factors during all three measurement times.

Tracking of the measured anthropometrical characteristics over the two-year study period was very high (r>0.880) (Table 3). The interperiod Spearman correlation coefficients for most of the measured 400-m front-crawl swim biomechanical and physiological values were also relatively high: time (r=0.867–0.984), v (r=0.768–0.950), SI (r=0.773–0.943) and Cs (r=0.781–0.839). The tracking of the SL (r=0.645–0.915), SR (r=0.609–0.928), VO_{2peak} (r=0.635–0.810) and ΔLa (r=0.581–0.727) were slightly lower. However, in contrast to the measured anthropometrical characteristics, the tracking coefficients of measured 400-m swim test values decreased slightly with increasing the time interval between the measurements (Table 3).

Table 3. Interperiod Spearman correlation coefficients of anthropometric, body composition, biomechanical and physiological values measured in male (n=29) swimmers at three time points

Variable	First measurement vs Second measurement	Second measurement vs Third measurement	First measurement vs Third measurement
Height (cm)	0.961	0.974	0.903
Body mass (kg)	0.976	0.982	0.933
BMI (kg/m^2)	0.901	0.947	0.905
Body fat%	0.935	0.928	0.880
FM (kg)	0.933	0.960	0.880
FFM (kg)	0.942	0.983	0.989
BMC (kg)	0.984	0.981	0.958
Total BMD (g/cm^2)	0.990	0.989	0.977
Spine BMD (g/cm^2)	0.981	0.963	0.952
Arm span (cm)	0.970	0.975	0.928
Time (s)	0.921	0.984	0.867
v (m/s)	0.863	0.950	0.778
SL (m/cycle)	0.796	0.915	0.645
SR (cycle/min)	0.647	0.928	0.609
SI (m^2 s/cycles)	0.885	0.943	0.773
Cs (kJ/m)	0.815	0.839	0.781
VO_2 (l/min)	0.635	0.810	0.773
ΔLa (mmol/l)	0.581	0.727	0.604

BMI-body mass index, Body fat% – body fat percent, FM – body fat mass, FFM – fat free mass, BMC – bone mineral content, BMD – bone mineral density, v – swimming velocity, SL – stroke length, SR – stroke rate, SI – stroke index, Cs – energy cost, VO_{2peak} – peak oxygen consumption, ΔLa – net increase of blood lactate

5.3. Development of physiological, biomechanical and anthropometrical parameters and swimming performance in young female swimmers

During the two-year follow-up study period, the age, height, body mass, body fat%, FFM, BMC, total BMD, arm span, and biological maturation values significantly increased during each year ($p<0.05$) (Table 4). However, the increases in the FM and spine BMD values between the second and third measurements, and that in the BMI value between the first and second measurement, were not significant ($p>0.05$). Performance time of the 400-m front-crawl swim significantly improved during each year (Table 5). Mean v, SL, SI, and Cs values of the swimming test were significantly improved only at the third measurement, whereas ΔLa was significantly increased after the first measurement and no changes occurred between the second and third measurements. In addition, VO_{2peak} was significantly increased after the second measurement.

Table 4. Mean (±SD) anthropometrical and body composition parameters in young female (n=26) swimmers over three measurement points

Variable	First measurement	Second measurement	Third measurement
Age (yrs)	12.7±2.2	13.6±1.9*	14.6±1.9*#
Height (cm)	160.9±9.3	163.0±8.6*	164.7±7.3*#
Body mass (kg)	50.3±9.2	52.8±8.7*	55.8±8.8*#
BMI (kg/m^2)	19.5±2.9	19.8±2.6	20.5±2.9*#
Body fat%	20.7±5.7	22.1±5.7*	23.2±6.4*#
FM (kg)	10.0±3.8	10.9±3.5*	12.0±4.4*
FFM (kg)	37.2±6.0	38.9±6.1*	40.1±5.3*#
BMC (kg)	2.0±0.4	2.1±0.4*	2.1±0.3*#
Total BMD (g/cm^2)	1.03±0.08	1.04±0.08*	1.06±0.06*#
Spine BMD (g/cm^2)	0.97±0.15	0.99±0.14*	1.02±0.13*
Arm span (cm)	163.9±9.4	166.4±7.8*	167.7±7.3*#
Tanner stage	2.3±0.8 (1–4)	3.0±0.8* (2–5)	3.5±0.6*# (3–5)

BMI-body mass index, Body fat% – body fat percent, FM – body fat mass, FFM – fat free mass, BMC – bone mineral content, BMD – bone mineral density
* Significantly different from the first measurement; p<0.05.
# Significantly different from the second measurement; p<0.05.

Table 5. Mean (±SD) biomechanical and physiological parameters obtained from the maximal 400-m front crawl swimming in female (n=26) swimmers over three measurement times

Variable	First measurement	Second measurement	Third measurement
Time (s)	373.9±39.2	366.8±41.6*	354.2±34.4*#
v (m/s)	1.04±0.10	1.05±0.11	1.09±0.10*#
SL (m/cycle)	0.94±0.12	0.94±0.13	0.99±0.11*#
SR (cycle/min^1)	67.8±5.3	67.9±4.9	66.7±3.9
SI (m^2/s/cycles)	0.99±0.22	1.00±0.24	1.09±0.20*#
Cs (kJ/m)	1.55±0.46	1.66±0.42	1.72±0.43*#
VO_{2peak} (l/min)	2.61±0.54	2.68±0.57	2.98±0.58*
ΔLa (mmol/l)	4.2±2.0	4.8±1.9*	4.8±2.4*

v – swimming velocity, SL – stroke length, SR – stroke rate, SI – stroke index, Cs – energy cost, VO_{2peak} – peak oxygen consumption, ΔLa – net increase of blood lactate
* Significantly different from the first girls; p<0.05.
# Significantly different from the second measurement; p<0.05.

The stepwise regression analyses revealed that SI (R^2>0.449; p<0.05), FFM (R^2>0.318; p<0.05) and VO_{2peak} (R^2>0.311; p<0.05) were the best predictors of the 400-m front-crawl swimming performance from the measured bio-mechanical, anthropometrical and physiological parameters at the first and second measurement times. At the third measurement point, the SI (R^2=0.322; p<0.05) from the biomechanical parameters measured, the BMC (R^2=0.203; p<0.05) from the anthropometrical values measured, and the VO_{2peak} (R^2=0.346; p<0.05) from the physiological values measured were the best predictors of 400-m front-crawl swimming performance. According to the stepwise regression analyses, the biomechanical factors (R^2>0.322; p<0.05) characterized best the 400-m swimming performance in young swimmers, followed by the physiological (R^2>0.311; p<0.05) and anthropometrical (R^2>0.203; p<0.05) factors at all three measurement times.

The tracking of the measured anthropometrical characteristics over the study period was relatively high (r>0.694), except for the body fat% (r>0.554) (Table 6). The interperiod Spearman correlation coefficients for the 400-m front-crawl

Table 6. Interperiod Spearman correlation coefficients of anthropometric, body composition, biomechanical and physiological values measured in female (n=26) swimmers at three time points

Variable	First measurement vs Second measurement	Second measurement vs Third measurement	First measurement vs Third measurement
Height (cm)	0.784	0.694	0.715
Body mass (kg)	0.978	0.944	0.927
BMI (kg/m^2)	0.937	0.835	0.772
Body fat%	0.800	0.781	0.554
FM (kg)	0.954	0.789	0.760
FFM (kg)	0.962	0.957	0.923
BMC (kg)	0.986	0.953	0.932
Total BMD (g/cm^2)	0.969	0.884	0.868
Spine BMD (g/cm^2)	0.981	0.930	0.884
Arm span (cm)	0.940	0.970	0.900
Time (s)	0.858	0.843	0.809
v (m/s)	0.941	0.902	0.903
SL (m/cycle)	0.915	0.861	0.896
SR (cycle/min)	0.855	0.684	0.687
SI (m^2 s/cycles)	0.878	0.885	0.830
Cs (kJ/m)	0.644	0.588	0.434
VO_{2peak} (l/min)	0.645	0.615	0.600
ΔLa (mmol/l)	0.705	0.530	0.455

BMI-body mass index, Body fat% – body fat percent, FM – body fat mass, FFM – fat free mass, BMC – bone mineral content, BMD – bone mineral density, v – swimming velocity, SL – stroke length, SR – stroke rate, SI – stroke index, Cs – energy cost, VO_{2peak} – peak oxygen consumption, ΔLa – net increase of blood lactate swim biomechanical values measured were also relatively high: time (r=0.809–0.858), v (r=0.902–0.941), SL (r=0.861–0.915), SR (r=0.684–0.855) and SI (r=0.830–0.885). In contrast, the tracking of the physiological values was slightly lower: Cs (r=0.434–0.644), VO_{2peak} (r=0.600–0.645) and ΔLa (r=0.455–0.705). Furthermore, in contrast to the measured anthropometrical and bio-mechanical characteristics, the tracking coefficients of the physiological values also decreased increasing with the time interval between the measurements (Table 6).

6. DISCUSSION

6.1. Peak oxygen consumption and metabolic energy cost of swimming in young swimmers

The backward-extrapolation technique was used to evaluate VO_{2peak} during the maximal 400-m front-crawl swimming bout (Costill et al., 1985; Zamparo et al., 2000). This technique allows us to assess VO_{2peak} in sport-specific conditions in athletes. The backward-extrapolation technique has been previously validated in front-crawl swimming, and it has been demonstrated as a reliable method for assessing VO_{2peak} in adult swimmers (Montpetit et al. 1981). The results of this study show that backward-extrapolation could also be used in young male and female swimmers during biological maturation, and allows us to consider bio-mechanical parameters of swimming technique in the assessment of VO_{2peak} in these young swimmers. It has to be noted, however, that the VO_{2peak} obtained using the backward-extrapolation technique was compared with VO_{2peak} measured using a maximal cycle-ergometer test. Although VO_{2peak} estimated from the cycle-ergometer test might underestimate VO_{2peak} attained in an in-water swimming test in young male and female swimmers, the results of different VO_{2peak} tests in our young swimmers were comparable (see Figure 1). The VO_{2peak} values (3.20±1.03 l/min) obtained using the backward-extrapolation technique in boys at the first measurement time (age: 13.0±1.8 yrs) were somewhat lower to those found in a mixed age group of 12- to 17-year-old male swimmers (3.66±0.54 l/min) after maximal 400-m front-crawl swimming (Zamparo et al. 2000). However, the in-water measured VO_{2peak} values at the third measurement time (age: 15.1±1.8 yrs) were already higher (3.94±0.76 l/min) (see Table 2) compared to the results of Zamparo et al. (2000) study. The results of our study suggest that, as in adult swimmers (Costill et al., 1985; Zamparo et al., 2005a), VO_{2peak} during front-crawl swimming in the swimming pool can be determined using expired gas samples collected during the first 20 s of recovery in young male and female swimmers.

The energy cost of swimming has usually been assessed from the contribution of the aerobic, anaerobic lactic and anaerobic alactic systems. However, in competitive swimming, the contribution rate of the anaerobic alactic system is quite low, as the majority of the events last more than 1 min (Rodriguez, 1999). Accordingly, in this study, Cs was computed from VO_{2peak} and net increases in blood lactate values after maximal 400-m front-crawl swimming distance (Zamparo et al., 2005a). Cs has usually been assessed at speeds substantially slower than those actually attained during competition (Capelli et al. 1998; Poujade et al. 2002; Zamparo et al. 2005a). Cs increases as a function of velocity (Capelli et al., 1998; di Prampero, 1986; Poujade et al., 2002; Zamparo et al., 2000) and in many studies has been assessed from the ratio of oxygen consumption and the corresponding speed in swimmers (Capelli et al., 1998; Kjendlie et al., 2004a,b; Zamparo et al., 2000). The complex interaction of other variables such as specific anthropometric parameters (Chatard et al., 1985) and swimming technique (Unnithan et al., 2009) can be the reasons why the evaluation of the energy cost of swimming appears to be rather challenging. In addition, different protocols (e.g., different swimming speeds) and different lengths of swimming distances (from 100-m to 400-m) that have been used to assess in-water oxygen consumption values during swimming make it also difficult to compare obtained results in our young boys and girls with other studies. To our best knowledge, no studies on children have been performed before which have used the backward-extrapolation technique in the evaluation of VO_{2peak} followed by the assessment of the energy cost of swimming in young swimmers. According to the results of our study, it may be suggested that the evaluation of the Cs using backward-extrapolation technique in VO_{2peak} assessment together with post-distance increases in blood lactate values could be used in the estimation of energy cost during swimming distance in young male and female swimmers.

The assessed Cs of 400-m front-crawl swimming bout increased throughout the three measurement points in boys from 13.0±1.8 to 15.1±1.8 years of age (see Table 2), while it was only significantly increased at the third measurement point in girls (see Table 4). No difference in Cs was found between the first (age: 12.7±2.2 yrs) and second (age: 13.6±1.9 yrs) measurement points in girls. This indicates that a slow increase in Cs at 12–14 years is followed by the acceleration from 14 to 16 years of age in girls. In accordance to our results, Poujade et al. (2002) reported that Cs increases between the ages of 12 and 14 years in boys, whereas Chatard et al. (1990) found no differences in this measure between 14 and 17 years. It has also been suggested that stroke mechanics decrease Cs in children with increasing age (Poujade et al. 2002). Furthermore, it has been argued that the lower Cs of swimming in younger swimmers could be related to changes in anthropometric parameters (Chatard et al., 1990), while Poujade et al. (2002) found no relationship between Cs and anthropometrical parameters. Differences in Cs could also reflect the differences in physical maturity and specific stroke parameters of swimming test. According to van Praagh (1997), the differences in Cs could also result from qualitative changes that occur during growth, such as muscle fibre characteristics, hormonal effects and/or neuromuscular maturation. It can be assumed that children who have reached puberty are already mature enough to produce more energy from anaerobic pathways, compared with less mature children. It is known that children accumulate less blood lactate than adults during swimming (Poujade et al. 2002) and the net blood lactate values after maximal 400-m front-crawl swimming in studied boys and girls were significantly higher at the second and third measurement points in comparison with the first measurement point (see Tables 3 and 4). On the other hand, there are some researchers who have studied the relationship between the energetic cost and the stroke parameters in adult male and female competitive swimmers (Costill et al., 1985) and found that SI appears to be one of the major determinants in middle-distance front-crawl events.

In summary, the results of our study suggest that backward-extrapolation method of assessing peak oxygen consumption after maximal 400-m front-crawl swimming could be used in testing for young competitive swimmers. The assessment of energy cost together with biomechanical parameters allows the evaluation of the swimming training efficiency.

6.2. Development of anthropometrical and performance parameters during biological maturation in young male and female swimmers

The present investigation analyzed longitudinally the development of swimming performance in biologically maturing young male and female swimmers. Swimmers usually start with heavy trainings before the onset of puberty and achieve international competitive level at a relatively young age (Costill et al., 1992). However, very few studies have investigated different aspects of swimming performance in swimmers younger than 12 years of age (Geladas et al., 2005; Poujade et al., 2002; Zamparo et al., 2000). It is necessary to study different parameters that might affect swimming performance in complex, taking into account various anthropometrical, biomechanical and physiological aspects of swimming. Furthermore, it is important to analyze these physiological and biomechanical characteristics in conditions similar to those of free swimming in a swimming pool (Poujade et al., 2002; Zamparo et al., 2000). This enables consideration of specific parameters when predicting success and designing specific training programmes in young swimmers. To our best knowledge, it appears that this study might be the first one to investigate the development of swimming performance in young male and female swimmers over two year period, taking into account specific factors which might affect their sport-specific performance. The present results demonstrated that biomechanical parameters characterized best the 400-m front-crawl swimming performance time in our specific groups of young male and female swimmers at all three measurement times over the two-year study period. In boys, biomechanical factors were followed by anthropometrical and physiological factors during all three measurements times. In girls, physiological factors were better predictors of swimming performance compared with anthropometrical parameters over two-year study period. Therefore, these results clearly demonstrate that the development of sport-specific technical skills is the most important part during the early years of swimming training in young swimmers. In addition, the tracking coefficients of measured swimming biomechanical characteristics together with the swimming performance time and the anthropometrical parameters in male and female swimmers were relatively high, while the tracking of the sport-specific physiological values was lower in both groups. These results further demonstrate that great emphasis should be on learning the correct swimming technique during the early years of training and the correct swimming technique learned during early years of swimming training is the basis for further development of sport-specific physiological measures during later years of swimming training.

One of the most important findings of the present investigation was that biomechanical parameters characterized best the 400-m front-crawl swimming performance, while SI was the best biomechanical predictor characterizing swimming performance in young male ($R^2>0.726$; $p<0.05$) and in female ($R^2>0.449$; $p<0.05$) swimmers at all three measurement times. In addition, the tracking coefficients of the all measured biomechanical characteristics in our study were relatively high for both boys and girls (see Tables 5 and 6), suggesting that it is important to have good stroke parameters already at the early years of swimming training. Unfortunately, to our best knowledge, there are only very few studies, which have used SI as a measure of swimming technique (Barbosa et al. 2005, 2010; Costill et al. 1985). In accordance with our results, recent study by Barbosa et al. (2010) also demonstrated significant relationship between swimming performance (200-m front-crawl swimming) and SI in 12-year old boys and found that the effect of SI on swimming performance is mediated by propulsive efficiency of body movement in the water. Similarly to adult swimmers over the 400-yard (365.8-m) distance (Costill et al. 1985), Barbosa et al. (2010) also suggested that SI could be used as an evaluation criterion of swimming performance in young swimmers on a regular basis. SI is an indicator of swimming economy since it describes the swimmers ability to move at a given velocity with the fewest number of strokes (Costill et al., 1985). SI increased significantly ($p<0.05$) in our young male (from 0.99±0.24 to 1.12±0.27 m^2/s/cycles) and female (from 0.99±0.22 to 1.09±0.20 m^2/s/cycles) swimmers after the two-year study period in a 400-m front-crawl swimming distance. However, SI and other measured swimming biomechanical parameters (v, SL and SR) did not increase significantly after the first year of measurement (see Tables 3 and 4). Consistent with our findings, the most rapid growth in swimming speed has been found to occur from 11 to 13 years of age in children, while a slow increase of the swimming speed occurs at 13–14 years, followed by the second acceleration from 14 to 16 years of age (Vorontsov & Binevsky, 2002). Taken together, the results of these studies suggest that it is very important to consider specific stroke-technique parameters when predicting success in young swimmers during biological maturation.

The beginning of serious trainings at the onset of puberty could suggest that anthropometric parameters together with body composition values might affect swimming performance to some extent (Chatard et al., 1985), since puberty is known to cause rapid growth/changes in those parameters (Baxter-Jones et al., 1995). In our study, regression analyses revealed that anthropometric values (height and arm span) in boys ($R^2>0.299$; $p<0.05$) and body composition values (fat free mass and bone mass) in girls ($R^2>0.203$; $p<0.05$) were the best predictors of the 400-m front-crawl swimming performance from the measured physical parameters. It has been suggested that though body mass in the water accounts for much of the cost of floating, fat free mass provides a better representation of the drag created by the movement of the body through the water (Costill et al. 1985). This may explain the relationship between swimming performance and body composition values in young female swimmers. Our results are also in accordance with Geladas et al. (2005) study, which also found significant relationship of swimming performance with body height and arm span in 12-year-old boys and girls. However, the swimming distance in Gelades et al. (2005) study was 100-m front-crawl swimming. In contrast, Saavedra et al. (2010) results indicate that age and specific fitness, particularly those related with aerobic and speed endurance, are main predictors of swimming performance and that anthropometrical and technical variables are less relevant. While Strzala et al. (2005) found that 400-m front-crawl swimming performance is mainly affected by anaerobic capacity and less by anthropometrical parameters in young 15–17 year old male swimmers.

Tracking coefficients of anthropometrical parameters were very high (see Tables 5 and 6), hence it is important to pay attention to the selection process of young male and female swimmers. It has been reported that anthropometric parameters track highly during puberty (Leppik et al., 2006) and early physical maturity of swimmers has been implicated to sport-specific selection (Baxter-Jones et al., 1995). In addition, it has to be taken into account that training does not appear to affect young swimmers physical growth and biological maturity (Baxter-Jones et al., 1995). However, young swimmers learn to control the structure and efficiency of movement while they grow up and mature in the process of a 5–7-year training programme. During this time they pass through prepubertal stages when rapid physical growth and motor development take place (Vorontsov & Binevsky, 2002).

In contrast to the measured anthropometrical and biomechanical characteristics, the tracking coefficients of the physiological values were relatively lower and decreased with the increasing time interval between the measurements in both groups of studied swimmers (see Tables 5 and 6). In accordance with our results, it has been suggested that it is rather difficult to predict how the aerobic power may develop throughout the puberty (Baxter-Jones et al., 1995). While VO_{2peak} increased significantly over the two-year study period in boys (from 3.20±1.03 to 3.94±0.76 l/min) and girls (from 2.61±0.54 to 2.98±0.58 l/min), the increase was not significant in girls between Time 1 and 2. Baxter-Jones et al. (1995) suggested that specific training effectively increases aerobic power above the increase normally attributed to the age and to the corresponding physical growth and maturation. This was also the case in our study, where an increase in aerobic power towards the end of puberty was more noticeable. Meanwhile, the tracking coefficients for VO_{2peak} were relatively lower in male and female swimmers in this study (see Tables 5 and 6) and consequently it is rather difficult to predict how VO_{2peak} may develop during puberty (Baxter-Jones et al., 1993). Accordingly, the development of VO_{2peak} may not be the most important parameter in predicting the development of swimming performance in young swimmers during biological maturation.

One of limitation of this study might be the relatively high variation in participants' age. But knowing the results of previous studies, our results do not change, if we had used different statistical methods (e.g. individual analysis and summing up individual changes). Relationships between different tested parameters might have been changed, but the main finding will be the same. However, according to the results of our study, where relatively similar performance predictors were related at three time points, it can be suggested that the effect of the age was relatively minor.

In summary, present results indicate that the improvement in swimming performance during physical maturing was mainly related to the improvement in biomechanical factors during the 2-year study period in young swimmers. Biomechanical factors were followed by anthropometrical and physiological factors in boys, and by physiological and anthropometrical factors in girls. In addition, the tracking coefficients of swimming performance time, stroke index and anthropometric parameters were very high, while the tracking of sport-specific oxygen consumption value was lower over the two-year study period.

7. CONCLUSIONS

1. The backward-extrapolation technique of assessing oxygen consumption after maximal 400-m front-crawl swimming could be used to evaluate peak oxygen consumption. The evaluation of metabolic energy cost of swimming using oxygen consumption and net increase in blood lactate concentration measured after swimming can be used to evaluate swimming training in young male and female swimmers;

2. Improvement in swimming performance during physical maturing was mainly related to increases in body height and arm span values among the anthropometrical parameters, improvement in sport-specific peak oxygen consumption value among the physiological characteristics, and improvement in the stroke index among the biomechanical parameters in young male swimmers.

3. Improvement in swimming performance during physical maturing was mainly related to increases in fat free mass and bone mass values among the anthropometrical parameters, improvement in sport-specific peak oxygen consumption value among the physiological characteristics, and improvement in the stroke index among the biomechanical parameters in young female swimmers.

4. Biomechanical factors characterized best the 400-m front crawl swimming performance, followed by anthropometrical and physiological factors during the two-year study period of biological maturation in young male swimmers.

5. Biomechanical factors characterized best the 400-m front-crawl swimming performance, followed by physiological and anthropometrical factors during the two-year study period of biological maturation in young female swimmers.

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SUMMARY IN ESTONIAN

Erinevate antropomeetriliste, füsioloogiliste ja biomehaaniliste näitajate mõju noorujujate ujumistulemusele

Sissejuhatus

Ujumises alustatakse tavaliselt raskete treeningutega enne puberteediea saabumist ja kõrge rahvusvaheline tase saavutatakse suhteliselt noores eas. Ujumistulemus on seotud erinevate antropomeetriliste, füsioloogiliste ja biomehaaniliste näitajatega. Nende näitajate mõju täiskasvanud ujujate ujumistulemusele on uuritud suhteliselt palju. Kuid pikaajalisi uuringud kehaliste parameetrite, füsioloogiliste näitajate ja ujumise tehnika vahel on noortel ujujatel tehtud vähe.

Ujumise aegset hapnikutarbimist on oluline mõõta spordispetsiifilistes tingimustes, mis annab mõõdetavatele parameetritele suurema usaldusväärsuse. Täiskasvanud ujujatel on leitud, et koormuse järgselt mõõdetud hapnikutarbimise näitajad on sobivad, et määrata hapnikutarbimist ujumise ajal, kuid antud meetodi sobivust lastele pole varem uuritud.

Uurimustöö eesmärk ja ülesanded:

Käesoleva töö eesmärgiks oli uurida spetsiifiliste füsioloogiliste, biomehaaniliste ja antropomeetriliste parameetrite mõju ujumistulemuse arengule noorujujate bioloogilise küpsemise ajal.

Käesoleva töö ülesanneteks olid:

1. võrrelda vees mõõdetud maksimaalse hapnikutarbimise näite laboratoorsel teel mõõdetud maksimaalse hapnikutarbimise näitudega ja arvutada ujumise energiakulu;
2. vaadelda spetsiifiliste füsioloogiliste, biomehaaniliste ja antropomeetriliste parameetrite arengut noorujujatel (poisid) nende bioloogilise arengu ajal;
3. vaadelda spetsiifiliste füsioloogiliste, biomehaaniliste ja antropomeetriliste parameetrite arengut noorujujatel (tüdrukud) nende bioloogilise arengu ajal;
4. leida millised parameetrid (antropoloogilised, füsioloogilised või biomehaanilised) mõjutavad kõige enam ujumise tulemust noorujujatel (poisid) nende bioloogilise arengu ajal;
5. leida millised parameetrid (antropoloogilised, füsioloogilised või biomehaanilised) mõjutavad kõige enam ujumise tulemust noorujujatel (tüdrukud) nende bioloogilise arengu ajal;

Uuritavad ja metoodika

Uuringus osales 55 noorujujat – 29 poissi (vanus 13.0±1.8 aastat, pikkus 163.3±11.9 cm, kehakaal 51.6±13 kg) ja 26 tüdrukut (vanus 12.7±2.2 aastat, pikkus 160.9±9.3 cm, kehakaal 50.3±9.2 kg), kes olid treeninud vähemalt 3 aastat ja osalesid treeningutel keskmiselt 7 korda nädalas. Uuritavatel viidi läbi kahe aasta jooksul kolm mõõtmist. Igal mõõtmise korral:

- mõõdeti peamised antropomeetrilised näitajad (pikkus, kehamass, käte siruulatus, kehamassiindeks);
- määrati bioloogiline vanus vastavalt Tanneri meetodile;
- sooritasid ujujad maksimaalse 400-m ujumise, peale mida mõõdeti maksimaalne hapnikutarbimine ning määrati sõrmeotsaverest laktaadi näitajad kolmandal, viiendal ja seitsmendal minutil. Hapnikutarbimise ja laktaadi näitajate alusel arvutati ujumise energiakulu. Ujumise jooksul määrati ujumise kiirus, tõmbepikkus, tõmbesagedus ning arvutati tõmbeindeks;
- kehakoostise parameetrid (rasvaprotsent, rasvavaba mass, rasva mass, luude mass ja luutiheduse näitajad) määrati DXA meetodil.

Esimesel mõõtmisel määrati ka maksimaalne hapnikutarbimine veloergomeetril, selleks et võrrelda seda ujumise järgselt saadud maksimaalse hapnikutarbimisega.

Järeldused

1. 400-m maksimaalse krooliujumise järgselt mõõdetud hapnikutarbimine on sobilik meetod määramaks noorujujate maksimaalset hapnikutarbimist ujumise ajal. Energikulu määramist, kasutades hapnikutarbimist ja laktaadi kontsentratsiooni muutust peale ujumist, võib kasutada ujumise ökonoomuses hindamiseks noorujujatel;
2. Ujumistulemuse paranemine noorujujatel (poisid) bioloogilise arengu ajal oli peamiselt seotud kehapikkuse ja kätesiruulatusega mõõdetud antropomeetrilistest näitajatest, spordispetsiifilise hapnikutarbimisega mõõdetud füsioloogilistest näitajatest ja tõmbeindeksiga mõõdetud biomehaanilistest näitajatest;
3. Ujumistulemuse paranemine noorujujatel (tüdrukud) bioloogilise arengu ajal oli peamiselt seotud rasvavaba massi ja lude massiga mõõdetud antropomeetrilistest näitajatest, spordispetsiifilise hapnikutarbimisega mõõdetud füsioloogilistest näitajatest ja tõmbeindeksiga mõõdetud biomehaanilistest näitajatest;
4. Kahe aastase uuringu jooksul mõjutasid noorjujate (poisid) 400-m rinnulikrooli ujumistulemust kõige enam biomehaanilised järgnesid antropomeetrilised ja füsioloogilised näitajad;
5. Kahe aastase uuringu jooksul mõjutasid noorjujate (tüdrukud) 400-m rinnulikrooli ujumistulemust kõige enam biomehaanilised näitajad järgnesid antropomeetrilised ja füsioloogilised näitajad.

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