ACTA KINESIOLOGIAE UNIVERSITATIS TARTUENSIS

VOLUME 4

ACTA KINESIOLOGIAE UNIVERSITATIS TARTUENSIS

4

UNIVERSITY OF TARTU

ACTA KINESIOLOGIAE UNIVERSITATIS TARTUENSIS

VOLUME 4

TARTU
1999

This journal is indexed in: Sport Discus Database

Printed by Tartu University Press
Tiigi 78, Tartu 50410, Estonia
Order No. 612

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

SCIENCE AND FOOTBALL

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ABSTRACT

The application of scientific principles to soccer is a relatively recent development. Soccer match-play imposes demands on both aerobic and anaerobic systems. The majority of distance covered by players in a game is 'off-the-ball'. The work-rate is influenced by physical fitness, positional role, environmental conditions and style of play. Patterns of play can be described using the techniques of notation analysis, thereby providing feedback to players and the coach. Players are often obliged to compete twice a week and are helped by adopting strategies to accelerate recovery from match-play. A systematic approach to training is needed throughout the year for optimal and sustained performance.

Key words: football, training, competition

INTRODUCTION

Soccer (association football) is unarguably the world's most popular sport. Its current spectator appeal worldwide is paralleled by its attractions as a professional career for those players who excel. Yet only in very recent years has there been an input of scientific information to the professional game. Many of the top national teams employ physiologists who play a major role in the preparation of players for competition, implementing nutritional strategies for

recovering between games and assisting medical staff in developing training programmes for rehabilitation from injury. They also take the lead in physiological assessment of players in both field and laboratory settings.

The growth of sports science support for soccer practitioners has followed the acceptance of sports science as an academic discipline. Indeed as sports science expanded to become an accepted field within its parent scientific disciplines (psychology, physiology and so on), its development extended to specific sports, notably football. The World Congress of Science and Football, first convened in Liverpool in 1987, is held every 4 years. The Vth World Congress is scheduled for Lisbon in 2003. Formal recognition of Science and Football as an academic discipline was marked in the United Kingdom with the instigation of the Diploma of Science and Football at Liverpool John Moores University in 1991. This programme was upgraded to a full-time BSc (Honours) degree in 1998. There have been a number of post-graduate research degrees awarded throughout the European Community countries for scientific work directly related to football. Furthermore, the vocational training programmes for coaches now more than ever includes appreciable scientific content in its curricula.

These developments testify to the increased awareness of the relevance of science to the field of sport. In this review research related to soccer is described in order to illustrate applications of science to the sport.

THE SOCCER CONTEXT

Competitive soccer at an elite level calls for a wide range of skills and abilities. The capability to control and pass a ball, kick and shoot with accuracy and power, win the ball in the air, execute tackles to perfection, dispossess opponents or dribble past them are some of the more obvious skills. Players who show tactical "awareness", move into space at exactly the right time, evade opposing formations or create opportunities to win matches where

there seemed to be none, are likely to do well in the game. Also relevant are the player's appreciation of what is happening within the game, a sense of the location of one's team-mates and the positioning of opponents, and above all anticipation of where the play is leading to — in other words, an ability to "read the game". These are some of the characteristics associated with soccer performance.

In contemporary soccer the elite player needs a firm foundation of systematic preparation in order to cope with the many demands that competitive matches impose on him. This is particularly so at the professional level where deficiencies in fitness will be readily exposed by the opposition.

Scientific principles can complement the expertise and judgement of the coach in the preparation of players to meet the demands of the game. This scientific support is now being utilised by many of the top European and South American professional teams. At least six clubs in the English Premier League employ sports science personnel during the 1998–1999 season and a number of others utilise sports science in training or in monitoring fitness. Nevertheless, it is reasonable to ask "what exactly are the physiological stresses and demands of soccer play and how in fact can they be measured?"

MOTION ANALYSIS

An indication of the demands of the game can be obtained by recording the detailed behaviour of players during the course of the game. This calls for objective, reliable and valid measures: video-recordings of one player at a time, followed by computerised tracking of his path (and actions) now fulfil these criteria. A significant database on the movements of individual players has been built up over the last 25 years in the "science and football" facility at Liverpool John Moores University [16, 22]. This bank of information provides evidence of a significant increase in the pace of play in the top European Leagues over this time, although the

speed-up did not become pronounced until the early 1990's. This coincided with the success of European club sides such as A. C. Milan, Juventus and Ajax Amsterdam whose players tended to play at a high tempo and put firm emphasis on all-round fitness. Changes in the rules of play which penalised time-wasting and promoted greater continuity of play parallelled this development.

Outfield players cover between 9 and 12 kilometres in a game, the majority of which is at submaximal or low intensity (walking, jogging, cruising), the ratio of low intensity (jogging, walking) to high intensity (sprints) events being 7:1 in terms of time. The activity profile of a World Cup striker covering 10–12 km in an English League First Division match is shown in Figure 1. Strenuous

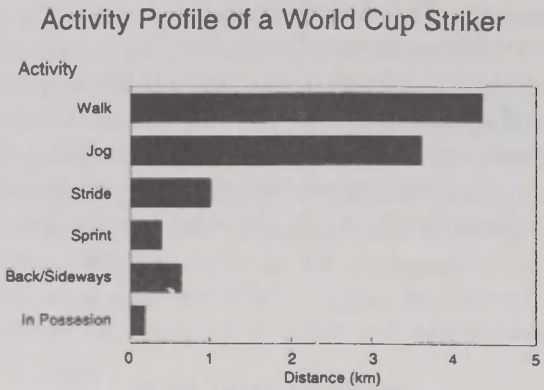

Figure 1. The distance covered by a World Cup striker when playing English League football according to positional role. These observations were made in 1994 a few months before he represented Ireland in the World Cup.

efforts (cruising and sprinting) are required every 30 seconds on average and all-out sprints averaging 15 metres in distance are made every 90 seconds on average. Each game entails over 1000 discrete activities, a change in activity every 5–6 seconds and a pause of 3 seconds once every 2 minutes [17]. The activity profiles are irregular in that the discrete actions rarely follow a par-

ticular pattern: nevertheless they are reproducible from game to game when the whole-game profile is taken into account. The most consistent observation is in the high intensity activity which seems to differ very little between games [3].

The overall distance covered represents a global index of players' work-rate during matches. Critically important is the timing of runs to support team mates, to assume strategic positions for defensive or offensive actions, to maintain the required shape of the team's formation and to entice opposing players out of position. Less than 2% of the total distance covered is with possession of the ball and a lot of direct involvement entails one-touch contact and accurate passing (see Figure 2). The exercise 'off-the-ball' incorporates accelerations and decelerations, abrupt changes of direction, angled runs and movements backwards and sideways. Most importantly, they incorporate actions directly involved in following the player on the ball and contesting possession.

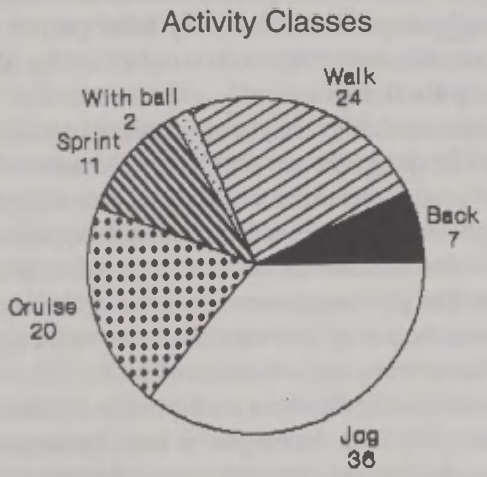

Figure 2. The percentage of the total distance covered in a game according to various categories of movement [22].

PHYSIOLOGICAL COMPONENTS OF SOCCER WORK-RATES

The majority of activities during soccer are aerobic in nature, consisting of submaximal exercise intensities. This has been corroborated by the finding of a significant correlation between maximal oxygen uptake and distance covered in a game [16]. This relation is strengthened when 'fitness' is indicated by performance in an intermittent endurance exercise test and results are correlated with selected aspects of work-rate within the game [2]. The greater distances are covered by mid-field players who tend to have the more impressive aerobic fitness test profiles. The lower distances among out-fielders are found in centre backs who tend to possess high anaerobic power (rather than high aerobic power) values. The variability (as evidenced by the standard deviation) is greater in the full backs, due to their greater flexibility than other roles. The same holds true for contemporary 'wing-backs', typically employed by a team that uses three central defenders. Anaerobic metabolism can deliver high energy output but for a very brief period and consequently high anaerobic capabilities are important for the high intensity activities of short duration.

The predominant activities may engage aerobic metabolism but the critical events in the game are dependent on anaerobic sources of energy. These events refer to the timing of movements (moving at exactly the right time), the execution of short quick movements (particularly by defenders and by forwards) to win the ball and agile movements to get past opponents. Important also is the ability to recover between bouts of exercise in order to be prepared for further all-out efforts when opportunities arise.

There is a tendency for the work-rate profile to decline towards the end of a game [18]. The decrement is least pronounced in subjects with high aerobic fitness but is also linked with a fall in glycogen stores contained within the leg muscles. Saltin [26] showed that 4 players who started a game with below normal muscle glycogen levels (as a result of training hard the previous day) were affected more by fatigue than were the 5 players with normal muscle glycogen stores per-match. The fatigued players also displayed a lower

number of sprints 'off-the-ball'. Carbohydrates stored in the liver and in skeletal muscles both provide the muscles with fuel for exercise, but carbohydrate broken down in the liver also furnish the cells of the central nervous system with glucose, thereby providing the brain with its energy source. An increase in goals scored towards the end of the game is further evidence of fatigue at this time [9]. Its explanation is likely to be accounted for by a complex of phenomena, including increased risk-taking by the team that is behind, a change in tactics due to the proximity of the end of the game, and lapses in concentration or mental fatigue. Deterioration towards the end of the game in mental performance related to soccer-specific decision-making is evident only in less-skilled players [13].

In the 1998 World Cup in France there was an increasing proportion of goals scored in the last 15 min of normal time. There was also an increased incidence of goals in the first 3 min following the half-time intermission [10]. Whether this was due to a lack of warm-up, a lapse in concentration or an increased level of arousal among one of the competing teams is impossible to say.

These trends towards 'fatigue' — have implications for the 'tempo' of the game and also for the nutritional strategies to last the entire 90 minutes of play. The needs for a high-carbohydrate diet in the build-up towards competition and the tapering of training loads in the two days before a match are highlighted, so that muscle glycogen stores are elevated pre-match and not emptied completely before the game ends. The benefits of a nutritional strategy to reduce fatigue have been demonstrated by various research groups. Kirkendall [11] investigated the effects of a glucose polymer supplement on work rate during soccer matches. Players were fed either 400 ml of the polymer or a placebo pre-game and at half-time. No effect was evident in the first half but distance covered in the second half was 25% greater and the distance covered at speed 40% greater for the glucose polymer condition. Foster *et al.* [8] also examined the effects of a glucose polymer solution on performance in successive matches of an indoor tournament. Players competed in a 50 min game, rested for 60 min and then played again. In the intermission, they consumed either a glucose polymer solution or a placebo. Those players who were given the glucose

polymer ran further and faster in the second game than players who received the placebo.

The energy provided in the glucose drinks delays fatigue, partly by saving muscle glycogen stores. Leatt and Jacobs [12] examined players who were given either 500 ml glucose polymer solution or placebo 10 min pre-game and at half-time. Glycogen reduction was greater in the placebo group than in those subjects given the glucose polymer, demonstrating that glucose ingestion decreased the net muscle glycogen utilization during soccer.

It is recommended that the carbohydrate content of the player's diet in the 2 days leading up to a match should be 55–60% of the total energy intake. It should be added that the pre-game meal should be light and eaten at least 3 hours before playing. After the game there is a need to replenish glycogen stores and the sooner that carbohydrate is provided afterwards, the better this is achieved. This can be made available in the dressing room or players' lounge once the players have showered: food in easily digestible form can be offered in conjunction with energy containing drinks.

The style of play will also influence the intensity of exercise during matches. The so-called "direct" method of play, pressurising opponents and moving the ball quickly into attack, increases the physiological demands on players. This approach was adopted by teams in the English professional soccer leagues in the 1980s and by the Republic of Ireland and Norwegian national teams, for example. International matches in South America entail players covering about 1 kilometre less than the players in the English Premier League where a slow methodical build-up of attacks is not favoured. Those players who were professionals in European Leagues (Spain, Italy and England) tended to exhibit the higher work-rates amongst the South American players [6]. Man-to-man marking is also more demanding than zone coverage. Experience is that these styles have been modified to cope with environmental stresses, such as altitude at the 1997 Copa America in Bolivia, and heat and humidity at the different venues of the 1994 World Cup in the USA.

Many game-related activities additional to locomotion around the pitch imply direct involvement in the game. Centre-backs and strikers jump to head the ball 20 times a game on average, the corresponding figure being 11 for full backs and 10 for midfield players. Tackles are made at roughly the same rate, being highest among defenders whose task it is to dispossess attackers of the ball, and lowest among the forwards [2]. The success rate of all skills (passing, tackling and so on) decreases as play progresses up the field from defence into attack, highlighting the increased pressure on the player with the ball as the play approaches the opponents' goal [21].

PHYSIOLOGICAL RESPONSES TO MATCH PLAY

The monitoring of physiological responses to soccer competition have entailed use of indirect or non-invasive methods and researchers have accepted the use of friendly or model games for this purpose. A key physiological question is 'how much energy do players use in a match?' Energy expenditures during match-play have been estimated from both work-rate profiles and heart-rate values [2]. The heart rates averaged throughout the game are then related to heart rate — oxygen consumption relationships determined for individual players in laboratory conditions. By utilising the respiratory exchange ratio corresponding to the predicted oxygen consumptions, the data to be converted into units of energy. Alternative methods such as expired gas collections from Douglas bags or meteorological balloons worn on the back, or use of portable radio telemetry systems carried as a back-pack, to measure oxygen consumption are impractical in real games. Chemical techniques such as the doubly-labelled water method may prove useful in the future in determining the habitual energy demands on footballers: these methods require players to drink an isotopic solution and later provide urine or blood samples for the energy turn-over to be calculated. The end result is a clear picture of whether the player being monitored is in energy balance over a period of about

a week and what the daily energy requirements to support both training and competition actually are.

Competitive soccer at top level entails an estimated energy expenditure of 4000–6000 kJ for a 70 kg player. This corresponds to about 70% of maximal oxygen uptake and is roughly the rate at which a marathon runner competes. The active muscles are not the only organs needing a steady supply of energy from the bloodstream: the brain is integrally involved in soccer play (in continually making decisions and tactical choices), glucose being its sole source of energy. Blood glucose levels do not identify hypoglycaemia as a major problem for the team as a whole, although the variability reported for glucose levels at the end of a game indicate one or two individuals may suffer [2]. It is likely that the repeated high-intensity bouts during the game will reduce muscle and liver glycogen stores appreciably. This again highlights the need to be adequately provided with carbohydrate before the game (i.e. the day before) and pay attention to restoring carbohydrate levels after the game. Circulating fatty acids are raised by the end of the game in much the same way as they are elevated in endurance runners but protein metabolism is not pronounced, protein contributing an estimated 3–5% to total metabolism. Consequently, the use of amino acids as energy supplements is not recommended for soccer players. Blood lactate levels vary throughout the game and at times may reach levels in excess of 8 mM [7]. It is thought that athletes can sustain exercise continuously up to a level corresponding to 4 mM: exercise above this intensity (at which breathing also begins to be challenged) will call for greater recovery periods so that the lactate produced can be cleared from the blood. Blood lactate levels recorded at the end of the game are dependent on the activities of the last 5 minutes. The lower blood lactate levels immediately post-match compared to observations at the end of the first half reflect both the increased proportional use of fat as a fuel for active muscles as the game progresses and the decline in intensity of effort as evidenced by the occurrence of fatigue.

During match-play heart rates tend to average about 170 beats/min. The variability about this value is small. Heart rates may remain at this level towards the end of the game, despite a fall

in work-rate. This may reflect the role of the circulatory system in regulating body temperature and preventing over-heating as well as for transporting oxygen to the active muscles.

The work-rate profiles tend to underestimate the energy requirements of the game. The main reason is that the changes in velocity and skills of the game are not taken into account in a calculation of distances covered. Moving sideways or backwards increases energy expenditure more than does normal locomotion [20]. Executing skills such as dribbling the ball also elevates energy expenditure and blood lactate more than does running at the same speed [19]. Consequently, these activities should be incorporated in training programmes where possible. A simple example is a progressive shuttle run where the player sprints from a scratch line to another 5, then 10, then 15, then 20 metres away, returning to the scratch line after each run, taking the ball with him and controlling it while he does so at speed.

NOTATION ANALYSIS

Notation analysis refers to a computer-aided method of examining patterns of play. Matches are recorded on video with the camera following the play. Details are played back by an operator who inputs information about the position on the pitch, the player involved and the outcome for each action on the ball. The data collected are collated and provide useful feedback for the coach. The most complex system currently available utilises six cameras fixed in an elevated position on the stand. Linked to a computer for post-match analysis, the system generates quantitative information about the work-rates of all players in a team and permits breakdown of patterns of play. In this way notation analysis can be used alongside motion analysis for the purpose of relating team effectiveness to physiological stress.

Notation analysis of the 1998 World Cup demonstrated how key performance characteristics could help separate successful teams from those that failed to get past the initial group stage [10].

The teams that reached the semi-finals were more effective in mounting attacks from regained possessions in their defensive sections and were more adept in gathering 'forward momentum' in a sequence of passes. In particular they were effective in penetrating defensive lines, the key creative moves originating in the area normally unoccupied between central midfield and the central defensive positions.

FOOTBALLERS' FITNESS CHARACTERISTICS

The fitness requirements for top soccer are many and varied, players needing the aerobic capabilities to sustain exercise for 90 (sometimes 120 minutes in cases of "extra-time"), the ability to accelerate quickly over short distances, decelerate or change direction without prior warning. Besides they must frequently generate high anaerobic power in jumping, tackling, shooting and so on. They need agility in order to change direction quickly, they need muscle flexibility in stretching for a ball and they need strong connective tissue to withstand physical trauma. Their muscular make-up reflects the repetitive kicking and force-generating actions of the game. Players tend to have more skeletal muscle mass than normal and have a more muscular or 'mesomorphic' shape. They cannot afford to carry any extra depots of adipose tissue which would both slow them down and adversely affect jumping power [15]. In this respect the footballer is unique, requiring a combination of different characteristics that are limiting factors in performance of other sports.

The physiological profiles of soccer players have been comprehensively reviewed by Reilly [16]. A physiological profile of a team provides detail on the overall state of fitness of the squad. This may vary according to the physical training regimens employed, the frequency of competition, the stage of the competitive season, and so on. It can help also in identifying strengths and weaknesses of individual players within the team. Physiological

attributes may be depressed in players without adequate fitness training, on return to play after injury, and at times of overtraining.

The maximal oxygen uptake ($\dot{V}O_2$ max) of professional football players does improve significantly in the pre-season period when there is an emphasis on aerobic training [15]. Further emphasis on improving the $\dot{V}O_2$ max adds little to the quality of play. When two teams of equal skill meet, the one with superior aerobic fitness would have the edge, being able to play the game at a faster pace throughout. Apor [1] provided data on Hungarian players which showed perfect rank-order correlation between mean $\dot{V}O_2$ max of the team and finishing position in the Hungarian First Division championship. The mean $\dot{V}O_2$ max for the first, second, third and fifth teams were 66.6, 64.3, 63.3 and 58.1 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively. Common factors such as stability in the team, avoidance of injury and/or suspension, and so on, help to maintain both $\dot{V}O_2$ max and team performance independently.

THE WEEKLY REGIMEN

Each week's training typically culminates in week-end competition. Usually, the weekly pattern is a build up to a mid-week peak and a tapering off in preparation for the match [24]. The lowered training load early in the week allows for recovery from the previous game and the aftermath of its physical contacts. The tapering is advised in view of the benefits of commencing each game with muscle glycogen levels replenished. This preparation can be complemented by nutritional strategies to bias the players' diet towards carbohydrates. The energy expended in a typical week in an England Premier League squad is illustrated in Figure 3. In this instance, matches were on Saturday with no training on Sunday.

This scheme has to be modified when two matches are scheduled in one week. In such events the training programme has to be curtailed in order that the players are not fatigued from training when they start the mid-week game. Nevertheless, the physical conditioning aspects of training cannot be abandoned and there

may be a need to focus on selective aspects of fitness in these short interim periods.

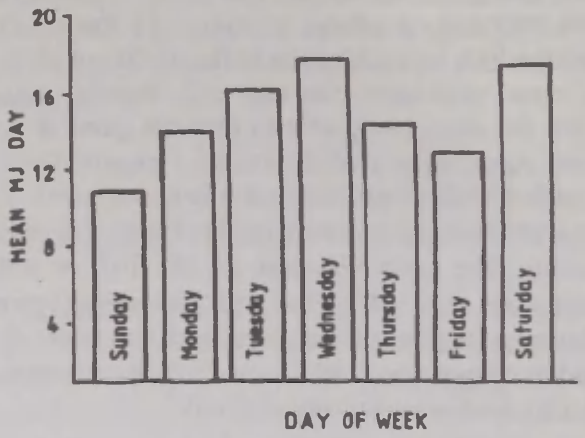

Figure 3. The energy (MJ/73 kg) expended by soccer players in a typical week incorporating a competitive match on Saturday [24].

There may also be a need to identify players who need supplementary or individualised training. This may occur when fitness profiling helps to isolate weaknesses in particular players. Players engaged in rehabilitation programmes need special attention so that their recovery can be optimised and thus avoid returning to competition too soon.

Time of day at which training is conducted is also a factor. Gross muscular performance tends to peak at about 18:00 hours when body temperature is at its daily high point [25]. Common practice among professional teams is that training is planned for the morning whether matches are in the afternoon or in the evening. Training is conducted in the morning so as to control players' habitual activity more easily rather than for chronobiological reasons which consider the human's body clock. Whilst evidence would support skills acquisition sessions for morning time, strength training sessions are best executed in the late afternoon and evening when muscle strength reaches its day-time peak. This

time of day would also help avoid risks of dehydration and hyperthermia in hot countries.

There are many components to the training stimuli for soccer. The various categories comprising the entire training programme are shown in Figure 4. The percentage allocated to each category is averaged over a full season and masks the occasions when emphasis is placed on a particular mode of conditioning.

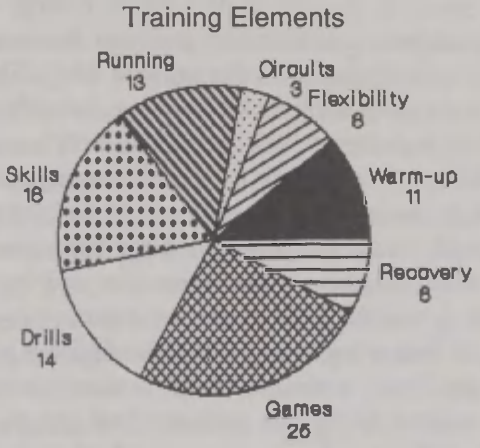

Figure 4. The breakdown of soccer training into discrete components. The values shown represent the percentage of time allocated to each of the categories over a full season's training [15].

RECOVERY FROM MATCHES

During certain periods of the season soccer players may have to take part in 3 (or even 4) games in 8 days, notably if engaged in European club competitions in mid-week and in their own national leagues at week-ends. At times of congested fixture lists they may be required to play 2 games within 3 days. It is imperative in such circumstances to adopt strategies which optimise recovery between matches.

Immediately post-game an active low-intensity warm down accelerates recovery processes. Whilst warm down procedures are readily adopted in many sports, they are not yet part of the soccer playing culture. Players may also have reduced glycogen stores in their leg muscles at the end of a match. It is important that the restoration of carbohydrate stores is commenced in the first 2 hours of finishing a game as glycogen resynthesis can be optimised at this time. Fluid replacement is also urgent since players may lose 2–3 hours in sweat in the course of a game. Energy and electrolyte drinks offer the best combination and can be complemented by making solid carbohydrate food available [14]. The regeneration can be continued with a high carbohydrate breakfast the next day, which might include cornflakes and bread with bananas, for example. Up to 600 g of carbohydrate should be ingested the day following a match, though this quantity might be exceeded in players with a high work-rate or possessing a large body mass.

Light training at submaximal intensities can be performed the day following a match. Delayed onset muscle soreness generally peaks 48 hours following exercise which entails repetitive "stretch-shortening cycle" movements. These actions occur in soccer in stretching to tackle, decelerate, kick the ball and in other contexts. Plyometric training employs exercises which incorporate stretch-shortening cycles and offers protection for 3 weeks or more against this form of muscle soreness [4]. Delayed onset muscle soreness doesn't seem to be a major problem with soccer players who are well conditioned. Nevertheless, strenuous plyometric drills should be avoided in between matches that quickly follow one another so that 'delayed onset muscle soreness' is not accentuated.

Deep-water training provides one method of maintaining fitness during an intense period of competition. This training mode entails various running actions in the deep end of the pool, the athlete normally wearing a buoyancy jacket. The method appears to be effective in aiding rehabilitation and as subjects can attain about 70% $\dot{V}O_2$ max when running in deep water, it would provide a strong stimulus in days of recovering from match stresses [5]. It has been used between tournament matches by Rugby Union teams and also by soccer teams participating in the Euro 96 champion-

ships in England. One particular advantage of deep-water running is that impact is reduced and spinal loading is decreased. This method has potential for clubs with access to swimming pool facilities.

SEASONAL VARIATIONS IN TRAINING

The more intense training regimens tend to be employed in the pre-season conditioning of players. This is largely due to the need to counteract the detraining effects that accrue between competitive seasons. Players who maintain a low intensity programme during the off-season manage to retain aerobic and muscular fitness relatively well in addition to controlling their body weight.

Pre-season conditioning programmes tend to emphasise endurance and aerobic fitness at the expense of muscular strength. Consequently players may commence the competitive period with sub-optimal muscle strength and therefore an increased risk of injury due to muscle weakness [23]. The tendency can be corrected by incorporating a balance of training stimuli in the pre-season training. During the competitive season players may frequently have to compete twice in one week. In such an event a considerable training stimulus is provided by playing the game. Once mid-season is reached a primary objective should be to maintain the fitness level already acquired to the end of the competitive season. This does not necessarily apply to the whole team, since some players may require additional training in cases of returning to the squad following injury, for example.

OVERVIEW

Physiological investigations have increased our understanding of the stresses associated with playing the game of soccer. The intensity of exercise during elite play has placed aerobic fitness as a

major requirement, although anaerobic efforts are emphasised in activities immediately around the playing actions. The physiological demands vary with positional role, styles of play and environmental circumstances. Cultural and national factors, independent of these also influence the pace at which matches are played.

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

REHYDRATION AND RECOVERY AFTER EXERCISE

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INTRODUCTION

Consistent, intensive training is the key to improved performance in most sports, and nutritional support of athletes aims to ensure that interruptions to the training program are minimised. Competition in most sports involves intensive effort, and recovery in preparation for the next competition or to return to training is equally important. Many different factors may contribute to fatigue during prolonged intense exercise, but in practice, depletion of the body's limited carbohydrate stores and dehydration are the two factors that most commonly limit exercise capacity. The need to replenish fuel stores rapidly and completely in the recovery period by eating a high carbohydrate meal is well recognised, and is an important part of every athlete's nutritional strategy. Effective restoration of fluid and electrolyte balance is no less important, but is often neglected.

For most athletes, some degree of dehydration is an undesirable but inevitable consequence of the need to perform hard physical exercise in training. This occurs in many situations, but is always worse in hot weather: sweating is effective at limiting the rise in body temperature in these conditions, but will result in the loss of water and electrolytes from the body. There are, however, also situations in weight category sports where dehydration is deliberately induced to enable the individual to achieve a target weight that allows them to compete in a weight class below their normal weight. Major depletion of the body's water stores is then followed

by competition, what athletes should be at the peak of their physical capability. The athlete who incurs a significant level of dehydration during exercise or who begins exercise in a dehydrated state will not be able to achieve their best performance. In these conditions, there is also a serious risk of heat illness, and recent deaths among American College wrestlers making weight for competition show that this is not just a theoretical risk. An effective fluid replacement strategy is vital.

FLUID BALANCE

Water is the largest single component of the normal human body, accounting for about 60% of body mass in lean men: The value is slightly less in normal women and overweight men because of their higher body fat content. Water also has a higher turnover rate than any other body component, with about 5–10% of total body water being exchanged every day in the sedentary person living in a temperate climate. In spite of this high turnover rate, the body water content is maintained within very narrow limits, seldom fluctuating by more than a few percent. The body water content of healthy individuals is maintained on a daily basis by a number of endocrine factors which control intake and output of both water and electrolytes. Vasopressin and the renin-angiotensin-aldosterone system are hormone control mechanisms which maintain the osmolality, sodium content and volume of extracellular fluids, and play a major role in the regulation of water balance. There is a continuous loss of water from the skin and respiratory tract, and intermittent losses from the kidneys and gastrointestinal tract. The kidneys regulate water and solute excretion in excess of the obligatory urine loss: they can excrete excess fluid, but can compensate to only a limited extent for an inadequate intake. Water intake occurs in the form of food and drink, with the sensation of thirst as the primary factor controlling intake. Daily fluid intake in man is usually in excess of perceived need and water balance is maintained by urinary losses [3].

Body water losses are increased in warm climates. Exercise in the heat is accompanied by significant losses of sweat as the body attempts to limit the rise in temperature that would otherwise occur. When the ambient temperature and humidity are high, there is a large increase in the athlete's water turnover. The sedentary individual living in a temperate climate normally has a daily water requirement of about 2–3 litres [8], although it is not easy to identify the origin of these and other textbook values. The need to keep cool by sweating in a hot, humid climate may increase this to 4–6 litres even for individuals who take no exercise. It is, of course possible to avoid heat stress even in hot climates, by taking advantage of air conditioned environments and avoiding exposure to the outdoor conditions.

Sweat losses during hard exercise in the heat may be as high as 2–3 l/h. Even in temperate climates, sweat losses may be greater than many athletes appreciate: in soccer games played in relatively cool conditions (about 10°C), for example, sweat losses may be as high as 2 l in a game lasting 90 min [12]. A table of sweat losses in various sports situations has been compiled by Rehrer and Burke [19]. For the athlete training hard for 2–3 hours per day in a hot climate, the daily water turnover may be 5–10 litres, and intakes as high as 15 litres per day have been reported by athletes training in hot climates and in military and occupational sitiuations. There are clearly some practical difficulties in meeting this demand. Particularly during the first few days of exposure to a hot environment, athletes from temperate countries find it difficult to increase fluid intake to match the increased losses and are likely to be chronically hypohydrated until equilibrium is re-established.

POST-EXERCISE REHYDRATION

Restoration of fluid balance after dehydration is influenced by both the volume of fluid consumed and by its composition. It is well established that plain water is not the best solution to be consumed following exercise to replace the water lost as sweat [1, 6, 18]. Re-

placement of electrolytes as well as water is essential for effective rehydration. Sodium is important in assisting effective rehydration: it is the major ion of the extracellular fluid and is also the major electrolyte present in sweat. If a large volume of plain water is ingested, plasma sodium concentration and osmolality fall, inhibiting further intake and stimulating a diuresis, even though the body may be in net negative fluid balance. If, however, sufficient sodium is added to the drink, plasma osmolality and sodium concentration do not decline, as some of the sodium remains in the vascular space. As a result, the circulating levels of vasopressin and aldosterone are maintained, and the diuresis that would otherwise occur is prevented. Where there are no restrictions on fluid intake, maintaining the plasma osmolality and the circulating sodium concentration also play a role in maintaining the drive to drink, and thus help to ensure that an adequate volume is consumed. Sweat potassium losses are small relative to the total body stores but it has been suggested that inclusion of potassium, the major ion of the intracellular fluid, in drinks consumed after sweat loss may aid rehydration by enhancing the retention of water in the intracellular space [17]. None of the other electrolytes lost in sweat is likely to be important from the perspective of water balance.

Several factors will influence both the volume of fluid consumed in the recovery and the effectiveness of that fluid in promoting rehydration and recovery. In comparison with the extensive investigations into the effects of fluid ingestion during exercise on performance, there is relatively little information on post-exercise recovery, but a picture is now beginning to emerge that allows some of the principles to be established and recommendations made to athletes. The studies on which these recommendations are based will first be reviewed.

DRINK COMPOSITION

The significance of sodium in drinks consumed after exercise for the purposes of rehydration after exercise-induced dehydration equivalent to 1.9% of body mass was investigated in six fasted

males who were euhydrated at the beginning of the study [14]. On four occasions, the subjects performed moderate-intensity intermittent exercise in a hot environment (30°C) until they had lost about 2% of their body mass. Then over 30 minutes period beginning 30 minutes after the end of exercise, a fixed volume of drinks with sodium concentrations of 2, 26, 52 and 100 mmol/l was consumed. To put these values in context, most soft drinks contain less than 2–3 mmol/l sodium, sports drinks typically contain about 20–25 mmol/l (although some have only about 10–12 mmol/l and some may have as much as 30 mmol/l), and oral rehydration solutions used for the treatment of diarrhoea in children usually contain about 50–80 mmol/l. The drinks were flavoured to minimise differences in taste. The volume of fluid consumed on each trial was 1.5 times the body mass loss incurred during the exercise period and this amounted to approximately 2 l.

For the next 5.5 hours all the urine produced was collected and measured (no other food or drink was consumed during the study period). Because the kidneys must continue to form urine during the recovery period, there is an ongoing loss of water from the body. If these losses are high, the body will quickly return to a dehydrated state, so effective rehydration requires that the ingested fluid is retained by the body.

The results of this study are clear that the volume of urine produced in the few hours after exercise is influenced by the quantity of sodium consumed. Urine output was greatest when the drink with the lowest sodium content was consumed and least when the 100 mmol/l drink was consumed, with the result that positive fluid balance was maintained after exercise only with the highest sodium concentration drink (Table 1a). In spite of the very large volume of fluid consumed, the high rate of urine output with the low-sodium drinks meant that positive fluid balance could not be maintained. Considering the small volumes that athletes normally drink during training or competition (perhaps in the region of 300–400 ml/h) the difference in net fluid balance between the different trials is relatively large. Between the drinks with the highest and lowest sodium concentrations, there was a difference in net fluid balance of 787 ml at the end of the study period.

Preservation of the plasma volume is important for the individual's capacity to exercise and to regulate body temperature. In this experiment, blood samples were collected before and 30 min after the dehydration period (immediately before the drink was consumed) and then at intervals until 5.5 h after the end of the rehydration period. Plasma volume, calculated from changes in haemoglobin and haematocrit levels using the formulae of Dill and Costill [2], decreased with dehydration (by about 4%) and increased following rehydration on all trials. This increase after exercise was less rapid with the 2 $mmol \cdot l^{-1}$ beverage; 1.5 hours after the end of the fluid ingestion period, the increase in plasma volume was 6.8% on this trial, but the plasma volume had expanded by 12.4% and 12.0% with the 52 and 100 $mmol \cdot l^{-1}$ drinks respectively. There was no significant difference in the change in plasma volume between trials 5.5 hours after the end of the rehydration period, but there was a strong tendency for it to be related to the sodium content of the drinks.

Table 1. Volume of urine produced following drink ingestion. Also shown is the fluid volume consumed. Values are mean (SEM)

	Drink			
a)	0 mmol/l Na^+	26 mmol/l Na^+	52 mmol/l Na^+	100 mmol/l Na^+
Drink	2035 (81)	2027 (103)	2050 (102)	2067 (93) volume (ml)
5.5h urine	1316 (132)	958 (103)	627 (87)	551 (82) volume (ml)
b)	90 mmol/l glucose	60 mmol/l Na^+	25 mmol/l K^+	90 mmol/l glucose 60 mmol/l Na^+ 25 mmol/l K^+
Drink	1620 (74)	1620 (35)	1660 (49)	1640 (32) volume (ml)
6h urine	577 (116)	248 (33)	303 (68)	254 (26) volume (ml)

This same experimental procedure was repeated in a second study in which it was possible to collect and analyse all sweat lost by the subjects during the dehydration process [21]. The results of this study showed a very clear relationship between the net water balance measured at 5 or 6 hours after exercise, and the whole body net sodium balance (Figure 1). This study also showed that potassium balance is important, and the water balance was more closely

related to cation balance (expressed as the sum of sodium and potassium) than to sodium balance alone. Positive water balance was only achieved when positive cation balance was maintained.

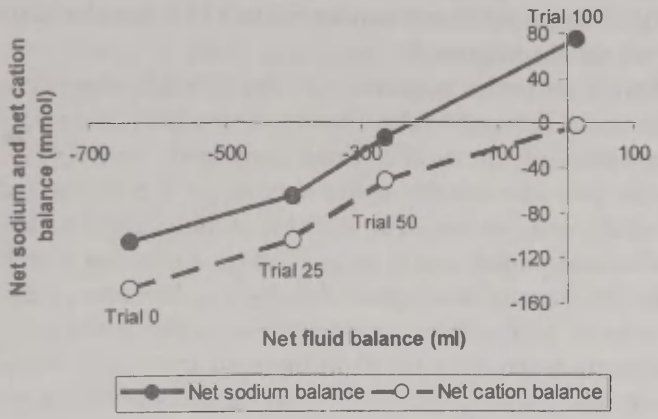

Figure 1. Net sodium and net cation balance (mmol) versus net fluid balance (ml) 5 and 6 hours after the end of the rehydration period.

In a third study designed to investigate the role of both sodium and potassium in rehydration drinks, eight male volunteers dehydrated by 2.1% of body mass by intermittent cycle ergometer exercise in the heat [13]. Subjects ingested either a glucose drink (90 $mmol \cdot l^{-1}$), a sodium containing drink (NaCl 60 $mmol \cdot l^{-1}$), a potassium containing drink (KCl 25 $mmol \cdot l^{-1}$) or a drink containing the glucose, sodium and potassium. The drinks were consumed over a 30 min period beginning 45 min after the end of exercise in a volume equivalent to the volume of sweat lost. This amounted to approximately 1.6 l and no other food or drink was consumed during the study. All the urine produced and excreted from the end of the rehydration period for the next six hours was collected.

A smaller volume of urine was excreted following rehydration when the electrolyte-containing beverages were ingested compared to the electrolyte-free beverage (Table 1b). A decrease in plasma volume of approximately 4.4% was observed with dehydration over all trials. After drinking, plasma volume increased on all trials

but the rate of recovery was slower after consumption of the KCl drink. However, by 6 hours after the end of the rehydration period, the increase was not different between trials; it amounted to 7.5(1.8)% for the glucose-electrolyte drink, 9.7(2.2)% for NaCl, 7.8(1.8)% for the KCl solution and 7.9(0.7)% for the drink containing all three components.

Although different amounts of electrolytes were consumed, there was no difference in the fraction of ingested fluid retained 6 h after ingestion of the drinks which contained electrolytes. It had been anticipated that there might be an additive effect of including both sodium and potassium in the rehydration drink, with sodium being retained preferentially in the extracellular space and potassium in the intracellular space. It may be, however, that as the drink volume consumed was equivalent to the volume of sweat lost, subjects were dehydrated throughout the entire study, even following the drinking period. It may not have been possible to further reduce the urine output when both sodium and potassium were ingested, over and above the reductions already induced when the sodium and potassium were ingested separately.

FLUID VOLUME CONSUMED

Any drink consumed after exercise-induced or thermal sweating must be in a volume greater than the volume of sweat that has been lost to even have a chance at restoring hydration status. This is because obligatory urine losses persist even whilst hypohydrated. In order to investigate this systematically, twelve male volunteers performed intermittent exercise in the heat in order induce a level of dehydration equivalent to a mean of 2.1% of their initial body mass [22]. Over 60 min, beginning 30 min after the end of exercise, drink volumes equivalent to 50%, 100%, 150% and 200% of the sweat loss were consumed. Six subjects consumed a drink with a relatively low sodium concentration (23 mmol/l), and six consumed a drink with a moderately high sodium concentration (61 mmol/l) in an attempt to investigate the possible interaction

between beverage volume and sodium content. Except for these drinks, nothing was consumed, and the entire volume of urine excreted was collected for six hours after the end of the drinking period.

With both drinks, the urine volume produced was influences by the total volume of fluid consumed; the smallest volumes were produced when 50% of the loss was consumed and the greatest when 200% of the loss was consumed. However, as a different fluid volume was consumed on each trial, a calculation of fluid balance status relative to the situation prior to the dehydration allows for easier comparisons than the total volume of urine excreted. With dehydration, individuals move into negative fluid balance and by drinking they return towards a positive fluid balance status, only if the volume consumed is greater than the sweat loss do they become positively hydrated; urine output moves them towards a state of negative fluid balance again (Figure 2, Table 2).

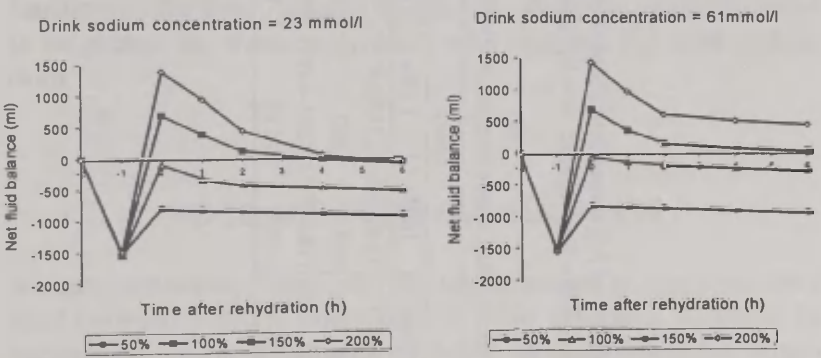

Figure 2. Net fluid balance (ml) over the course of the study. The left panel subjects consumed the 23 mmol/l Na^+ drink and the right panel subjects consumed the 61 mmol/l Na^+ drink. Trials A, B, C and D represent fluid volumes of 50, 100, 150 and 200% of the sweat volume losses respectively.

Table 2. Volume of urine produced following drink ingestion. Also shown is the drink composition and the volume consumed. For net fluid balance: 0 = euhydrated, + = hyperhydrated, – = hypohydrated. Values are mean (SEM) or median (range) as appropriate.

	Drink sodium concentration = 23mmol l^{-1}				Drink sodium concentration = 61mmol l^{-1}			
	Drink				Drink			
	50%	100%	150%	200%	50%	100%	150%	200%
Drink volume (ml)	746(17)	1448(30)	2255(83)	2927(81)	758(33)	1522(58)	2243(72)	3180(142)
6h urine volume (ml)	135 (114–240)	493 (181–731)	867 (263–1191)	1361 (1014–1984)	144 (124–162)	260 (137–376)	602 (350–994)	1001 (714–1425)
6h net fluid balance (ml)	–909	–528	–128	–135	–958	–286	+111	+427

Subjects were significantly hypohydrated throughout the recovery period when they consumed a volume equivalent to only half their sweat loss: whatever the composition, the volume ingested was inadequate to replace losses, and no amount of water conservation by the kidney could compensate for this. With a drink volume equivalent to that of the sweat loss, subjects were also hypohydrated because of the ongoing renal loss, but less so when the higher sodium beverage had been consumed. When the low sodium drink was consumed in a volume equal to double the sweat loss, subjects were still slightly hypohydrated 6 h after drink ingestion. With the high sodium drink, subjects had retained enough of the fluid to maintain a state of hyperhydration 6 h after drink ingestion when they consumed either 150% or 200% of their sweat loss.

Plasma volume was calculated to have decreased by approximately 5.3% with dehydration. Six hours after finishing drinking the general pattern in plasma volume change, irrespective of which drink had been consumed, was for the increases to be a direct function of the drink volume consumed: also, the increase tended to be greater for those individuals who ingested the high sodium drink.

FOOD AND FLUID CONSUMPTION

In many situations, there may be opportunities to consume solid food between exercise bouts, and in most situations it should be encouraged unless it is likely to result in gastrointestinal disturbances. To investigate the role of food intake in promoting rehydration, eight volunteers (5 male, 3 female) were dehydrated by 2.1% of body mass and then consumed either a solid meal plus flavoured water or a commercially available sports drink [15]. The volume of fluid in the meal plus water was the same as the volume of sports drink consumed. For 6 h after the end of the eating and/or drinking, the entire volume of urine produced and excreted was collected.

The volume of urine produced following food and water ingestion was almost 300 ml less than that when the sports drink was consumed (Table 3). Plasma volume decreased by 5.4% with dehydration over all trials and increased following rehydration on all trials; there was no difference between the two experimental conditions in the magnitude of this change (11.7(0.7)%) for the food plus water trial and (13.2(1.5)%) with the sports drink without food). The quantity of water consumed with both rehydration methods was the same, but the meal had a greater electrolyte content (Table 3). It seems most likely that the greater efficacy of the meal plus water treatment in restoring whole body water balance was a consequence of the greater total cation content.

Table 3. Volume of urine produced following drink ingestion. Also shown is the fluid volume consumed and the quantities of major electrolytes ingested. Values are mean (SEM) or median (range) as appropriate

		Meal + water	Sports drink
Fluid volume (ml)		2076 (131)	2042 (132)
Electrolytes ingested	Na^+	63 (4)	43 (3)
(mmol)	K^+	21 (1)	7 (1)
6h urine volume (ml)		665 (396–1190)	934 (550–1403)

ALCOHOL CONSUMPTION

Alcohol and caffeine are well-known for their diuretic properties and because of this it is usual to advise against the consumption of drinks containing these substances when fluid replacement is a priority. However, many people enjoy consuming these beverages, and where large volumes of fluid must be consumed in a relatively short time, a wide choice of drinks will help to stimulate consumption. Abrupt and complete cessation of caffeine intake may also provoke withdrawal symptoms in individuals accustomed to a regular intake, and it may not be wise to suggest this. In many

sports, particularly team sports, alcohol intake is a part of the culture of the sport, and athletes are resistant to suggestions that they should abstain completely. We therefore investigated the effect of consuming alcohol following exercise in the heat sufficient to induce dehydration equal to about 2% of body mass [20]. Over 60 min beginning 30 min after the end of exercise subjects consumed beer shandy (a peculiarly British drink produced by mixing beer with lemonade) in a volume equivalent to 150% of their mass loss. The test drinks contained 0, 1, 2 or 4% alcohol, but otherwise had the same composition.

Over the 6 h following drink ingestion the urine output was related to the quantity of alcohol consumed, but despite a tendency for the urinary output to increase with increasing alcohol intake, only with the 4% beverage did the increased value approach significance (Table 4). Thus, the hydration status was only marginally affected by the alcohol content of the drinks. The calculated decrease in plasma volume with dehydration was approximately 7.6% across all trials. With rehydration the plasma volume increased, but the rate of increase seemed to be related to the quantity of alcohol consumed; six hours after finishing drinking, the increase in plasma volume relative to the dehydrated value was 8.1(1.3)% with 0% alcohol, 7.4(1.1)% with 1%, 6.0(1.4)% with 2% and 5.3(1.4)% with 4%. It may be worth noting that the high sugar content of lemonade (10%) means that beer shandy has a carbohydrate content of about 5%, and this carbohydrate may play an important role in the restoration of muscle and liver glycogen stores after exercise.

Table 4. Volume of drink consumed and fraction of fluid retained 6 hours after drink ingestion. Values are mean (SEM)

	Drink			
	0%	1%	2%	4%
Drink volume (ml)	2178 (78)	2240 (60)	2275 (63)	2155 (51)
Fraction of fluid retained (%)	59.3 (6.4)	53.1 (4.5)	50.0 (6.6)	40.7 (5.6)

VOLUNTARY FLUID INTAKE

In all the studies described above, a fixed volume of fluid was consumed on all trials. In everyday situations however, intake will be determined by the interaction of physiological and psychological factors. In a study to examine the effect of palatability, together with the solute content of beverages in promoting rehydration after sweat loss, eight males exercised in the heat to lose 2.1% of their body mass [11]. Over a two hour period following exercise, subjects were allowed to drink as much as they wished of each of the test drinks: the drinks they received, each on a separate occasion, were an oral rehydration solution, aerated water, a commercial sports drink and an orange juice/lemonade mixture. The composition of these drinks is shown in Table 5.

Table 5. Volume of drink consumed and net fluid balance 4 hours after rehydration. Values are mean (SEM)

For net fluid balance: 0 = euhydrated, + = hyperhydrated, – = hypohydrated.

	Drink			
	glucose 90mM	aerated water sodium 60mM potassium 24mM	sports drink sodium 24mM potassium 4mM	orange/lemonade sodium 2mM potassium 24mM
Drink volume (ml)	1796(268)	1750(198)	2492(270)	2488(95)
4h net fluid balance (ml)	–123(251)	–474(136)	–135(146)	45(97)

Subjects drank a greater volume of the sports drink (2492 ml) and of the orange juice/lemonade mixture (2488 ml) than of either of the other two drinks (water 1750 ml: glucose-electrolyte drink 1796 ml), and this reflected the preference that subjects expressed for the taste of these drinks. There were large individual differences in the volume consumed. Immediately after exercise, the subjects were in negative fluid balance, but the volume consumed was sufficient to move them into positive fluid balance on all trials. Urine output was greatest with the low electrolyte drinks that were consumed in the largest volumes (the sports drink and the orange

juice/lemonade mixture), and was smallest after drinking the oral rehydration solution (Table 5).

These results demonstrate the importance of palatability for promoting consumption, but also confirm the earlier results which showed that a moderately high electrolyte content is essential if the ingested fluid is to be retained in the body. The benefits of the higher intake with the more palatable drinks were lost because of the higher urine output. Water was the least effective beverage, with a low intake and a relatively high loss in urine.

MENSTRUAL CYCLE EFFECTS — CONCERNS FOR FEMALE ATHLETES

A changing fluid balance status, due to the retention of water is reported by many women over the course of their menstrual cycle. This is due to the cyclical variation in the release of steroid hormones. It is possible, therefore, that changes related to the stage of the menstrual cycle may have an acute effect on fluid balance in the few hours after exercise-induced sweat loss. To investigate this five female subjects, each with a regular menstrual cycle exercised in the heat to dehydrate themselves by 1.8% of the body mass [16]. They did this at three different stages of their menstrual cycle (2 days before, 5 and 19 days after the onset of menses) and over a 60 min period beginning 30 min after the end of exercise they consumed the same quantity of the same beverage on each occasion: the volume consumed was 150% of the mass loss and the drink, a commercially available sports drink, was the same on all trials. For six hours after the end of the rehydration period, the entire volume of urine excreted was collected and measured. There was no difference in the volume of urine produced (Table 6), and hence in the volume of the ingested fluid that was retained at the different stages of the menstrual cycle. These results suggest that the acute replacement of volume losses incurred by sweat loss due to exercising in the heat are not affected by the normal, regular menstrual cycle. Therefore, women seem not to be disadvantaged when rapid

and complete restoration of exercise-induced sweat loss is required.

Table 6. Volume of urine produced following drink ingestion. Also shown is the volume of drink consumed. Values are mean (SEM) or median (range) as appropriate

	Stage of menstrual cycle		
	2 days before the onset of menses	5 days after the onset of menses	19 days after the onset of menses
Drink volume (ml)	1662(87)	1550(77)	1392(108)
6h urine volume (ml)	714(469–750)	476(433–639)	534(195–852)

CONCLUSIONS

Complete restoration of fluid balance after exercise is an important part of the recovery process, and becomes even more important in hot, humid conditions. If a second bout of exercise has to be performed after a relatively short interval, the speed and effectiveness of the rehydration process becomes of crucial importance. Rehydration after exercise requires not only replacement of volume losses, but also replacement of the electrolytes (primarily sodium) lost in the sweat. The electrolyte composition of sweat is highly variable between individuals and over time in the same individual. Although rehydration may be optimised by relating electrolyte intake to the loss, the difficulties involved in assessing loss make this virtually impossible to achieve in a practical situation. However, provided that the volume intake is sufficient and that renal function is not impaired, any excess sodium ingested will be lost in the urine as the kidneys restore equilibrium.

Sweat composition not only varies between individuals, but also varies as exercise proceeds and is further influenced by the state of acclimation [23]. Typical values for sodium and potassium concentrations are about 50 mmol/l and 5 mmol/l respectively. Drinks intended specifically for rehydration should therefore probably have higher electrolyte content than drinks formulated for con-

sumption during exercise [10]. Where sweat losses are large, the total sodium loss will be high: 10 litres of sweat at a sodium concentration of 50 mmol/l amounts to about 29 g of sodium chloride. This is far in excess of the mean UK daily intake of about 6 g for women and 8 g for men [7]. Although concerns are often raised about a possible association between dietary salt intake and hypertension, a moderate excess of salt intake would appear to be beneficial as far as hydration status is concerned without any detrimental effects on health provided that fluid intake is in excess of sweat loss and that renal function is not impaired.

It is clear from the results of these and many other studies that rehydration after exercise can only be achieved if sweat electrolyte losses as well as water are replaced. The Oral Rehydration Solution (ORS) recommended by the World Health Organisation for the treatment of acute diarrhoea has a sodium content of 60 to 90 $mmol \cdot l^{-1}$ and a potassium content of about 25 $mmol \cdot l^{-1}$ [4], reflecting the high losses which may occur in some types of diarrhoea. In contrast, the sodium content of most sports drinks is in the range of 10–25 $mmol \cdot l^{-1}$ [9] and in some cases is even lower. Most commonly consumed soft drinks contain virtually no sodium and these drinks are therefore unsuitable if consumed without electrolyte-containing food when the need for rehydration is crucial. The problem with a high sodium concentration in drinks is that some people find the taste undesirable, resulting in reduced consumption. However, drinks with a low sodium content are ineffective at rehydration and will also reduce the stimulus to drink. Furthermore, it is possible with a suitable formulation to mask the saltiness of drinks.

Addition of an energy source is not necessary for rehydration although a small amount of carbohydrate may improve the rate of intestinal uptake of sodium and water, and will improve palatability. Where sweat losses are high, rehydration with carbohydrate solutions has implications for energy balance. Ingestion of 10 litres of soft drinks will provide approximately 1000 g of carbohydrate, equivalent to about 4000 calories. The same volume of sports drinks will supply about 2500 calories. The volume of beverage consumed should be substantially greater than the volume of sweat lost in order to make a provision for the ongoing obligatory urine

losses, and palatability of the beverage is a major issue when large volumes of fluid have to be consumed. Although is has been recommended in the past that 1 litre of fluid should be ingested for each kilogram of mass lost, it would seem prudent to ingest at least 1.5 times the amount of sweat lost.

Although water alone may be adequate for rehydration when food which will provide electrolytes is also consumed, there are many situations where intake of solid food is avoided. This is particularly true in weight category sports where the interval between the weigh-in and competition may be short, but is also the case in events where only a few hours intervene between succeeding rounds of the competition. In these situations, an adequate amount of electrolyte must be present in the drinks consumed.

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

TALENT DETECTION AND TALENT DEVELOPMENT: KINANTHROPOMETRIC ISSUES

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INTRODUCTION

Youth sports in general, and more specifically competitive sports for young children and adolescents, is an important phenomenon in today's society, as demonstrated by a lot of discussions in governmental bodies, educational environment, and attention within the media. Also, within the sports clubs and sports federations, the importance of high qualified guidance of young talented children, based on scientific knowledge and evidence, becomes more and more stressed. Within this context, reference is given to the book *"The Child and Adolescent Athlete"* (Volume 6 within the prestigious series of the "Encyclopedia of Sports Medicine"), recently published under the auspices of the Medical Commission of the International Olympic Committee, in collaboration with the International Federation of Sports Medicine [3]. From a medical-scientific viewpoint, a lot of attention is given on some negative influences of intensive training and competition on the growth and development of the young child. In the past, competition sports were mostly organized for adults; however, today, more and more intensive training, on a very high level, starts at a very young age, and more and more youngsters are involved in competitive sports. Examples are frequently seen in gymnastics in which pre-pubertal

girls compete at the highest level in national and/or international championships, starting at an age around 4–5 years [17, 43, 44]. However, competing at the highest level requires children who are in some cases "exceptional", with other words, these kids are to be "talented". In this context, talent detection, and especially talent development and talent guidance, are important aspects within an active and well-conceptualized sports programme and sports policy. The identification of talented youth has therefore to be done on a scientific basis within a society-relevant and ethical context. Furthermore, the guidance and development of talented children is of importance and has to be based on scientific knowledge and background. It has to be stressed that the concept of "sports talent" is multi-factorial, i.e. that all factors such as morphological, physiological, motor-functional, psychological, and socio-cultural has to be taken into account [e.g. 26, 55].

In this article, talent detection and talent development will be reviewed from a kinanthropometric viewpoint. Kinanthropometry refers to the "quantitative interface between structure and function", and is, as such, the scientific discipline focussed on the measurement of men. More specifically, kinanthropometry refers to the measurement of human size, proportion, somatotype, body composition, maturation, and gross motor function [25, 57].

DETECTION AND DEVELOPMENT OF TALENT: THE IMPORTANCE OF KINANTHROPOMETRIC PARAMETERS

During the last decades, a lot of scientific studies have focussed on the identification and selection of future elite athletes [e.g. 8, 26, 44, 48, 49, 55]. This is not "accidental", but a "necessity". Because children who wants to reach the 'highest' level in a certain sport, have to start training at a young age, have to train many hours per week, for several years, very intensively, and that within a social and emotional stressed environment. It has to be clear that during this long process, these children have the right to be guided by a

team of highly qualified specialists (e.g. physicians, trainers, coaches) within an optimal environment, both infrastructurally and socially. It is clear that such special "conditions" can only be offered to a "selected" (this means relatively small number) group of children. Thus, selection and development of 'gifted' (= talented) children is an important aspect within a well-developed sports policy. In this article, we will not focus on the different "talent systems" and "talent theories" which are well-described and well-documented in the literature [e.g. 7, 26, 33, 41, 49, 54, 55, 63].

Talent identification, and further on talent guidance and talent development, can be done very differently, ranging from the simplest way where the coach "detect" the most talented children on the basis of his/her "eye", to the most sophisticated way based on an extended battery of tests, which are scientifically set-up and validated. Extreme examples of such "batteries" were used in some previous East-European and the GDR selection programmes [see e.g. 26, 41, 44, 55].

Well-developed "screening programmes" or "detection batteries" consists of different items of which the "morphological" (or kinanthropometrical) parameters are of real importance, besides health-related, physiological, motor-functional, and psychological ones [7, 27, 29, 33]. An overview of items necessary for talent detection and talent development is given in Table 1.

Table 1. List of items necessary within the talent identification and talent developmental process

* Health status
* Genetic basis
* Time spent in sport
* Maturity
* Physical capacities
    - — Morphological assessment
        - ° Somatotype
        - ° Size / Body composition
        - ° Proportionality
    - — Posture
    - — Basic Motor Abilities (flexibility, strenght, power, speed)
* Functional capacity: Physiological and Motor Function Tests
* Psychological profile

(adapted from Bloomfield [7]; and Komadel [33])

The importance of kinanthropometric parameters (Maturity; Physical capacities) within the whole process of talent development is based on the fact that: (1) sports performance in youth is for a great part related to both physical and maturational characteristics [4, 5, 42, 45], and (2) these parameters show a relative high degree of heritability and predictability [16, 38, 40, 47, 53]. Both these aspects are of importance within the talent detection and developmental process. Also, from a medical point of view, a "suitable physique" for a certain kind of sport is stressed, based on the fact that "physique", besides others, can be an "etiological" factor for future sports injuries [2]. This is clearly illustrated in a study on elite female gymnasts in which heavier, taller and more robust girls are more characterized by a positive ulnar variance (ulnar overgrowth) leading to wrist pain, compared to their lighter and smaller peers [18]. Also, in a recent published statement of the American College of Sports Medicine [1] concerning "The prevention of sports injuries of children and adolescents", the importance of a suitable build is stressed: "... *if possible, a child or adolescent should be counciled toward sports that are realistic given the individual's body type* ..." (p.3). Because of their importance and applicability within the talent detection and talent development process, we will focus on the following items: (1) the assessment of the maturity status; (2) the prediction of adult stature; (3) the estimation of the somatotype; and (4) kinanthropometric profiling.

1. The assessment of the maturity status

It is well-known that children with the same chronological age show a great variability in their developmental or maturational status. Therefore, the estimation of the maturity status of the growing child is an important parameter, which has to be incorporated in all talent detection procedures [7]. Both, morphological as well as motor-functional characteristics (and thus also sports performance), are to some degree related to the developmental age of the child, especially during the adolescent growth spurt. It is a

well-known phenomenon that early-maturers are heavier and taller, and do better perform on most motor skills compared to their late mature, age-related peers [4, 5, 42]. Important within this context is the observation that many trainers and/or coaches "select" the early-mature youngsters, because these children perform better in their particular sport compared to late-maturers [7, 27]. To reduce this potential competitive inequality (size, strenght, and skill differences), often seen in youth competition, Malina and Beunen [45] advocate to "match" youngsters by body size and biological maturity status, rather than on the chronological age of the participants.

Several techniques to estimate the growth and maturity status of children are at hand [see 46, for an overview]. The most accurate method is the assessment of *skeletal age* on the basis of an X-ray of the left hand and wrist according to the Tanner-Whitehouse II Method [60]. However, this method is not a practical system applicable in the field, and not directly allowed from a medical-ethical point of view. A less 'invasive' maturity indicator is the estimation of percentage of adult stature [6]. In girls, the age of menarche, the first menstrual period, is often used as an indicator for sexual maturity. Detailed information concerning the relationship between age at menarche and sports performance, and the factors influencing this relationship, is given by Malina [39].

2. The prediction of adult stature

Besides other anthropometric dimensions, stature, as an overall indicator of body size, is an important parameter to be used in the talent identification process. It is well-known that top level athletes of different sports or disciplines are characterized by differences in body height. For sports as basketball, volleyball, rowing and water polo, it is an advantage to be tall, whereas a small stature is advantageous in sports as e.g. gymnastics, diving and figure skating. Scientific studies investigating the relationship between stature and sports performance are well documented [e.g. 10, 31, 32, 51].

Several techniques are at hand to predict adult stature: (1) based on the estimation of skeletal age [60]; (2) the use of "less-invasive" regression formulae based on anthropometric parameters [6]; and (3) based on the mean stature of the parents of the young athlete [33]. An overview of some formulae for the prediction of adult stature is given in Table 2. It has to be taken into account, however, that there is a certain degree of 'estimation error', connected to all these prediction formulae, ranging from about 2 cm to 4 cm.

Table 2. Overview of some formulae for the prediction of adult stature (AS)

1) On the basis of skeletal age [60]
* Formula for an 11-year old boy:
AS = 78 + 1.11 (stature, cm) – 3.6 (age, year) – 1.85 (skeletal age, year)
* Formula for a 12-year old, pre-menarcheal girl:
AS = 89 + 0.96 (stature, cm) – 1.7 (age, year) – 3.9 (skeletal age, year)
* Formula for a 12-year old, post-menarcheal girl:
AS = 29 + 1.02 (stature,cm) – 3.5 (age, year) – 0.23 (skeletal age, year) + 1.6 (age at menarche, year)
2) On the basis of anthropometric dimensions (only for boys) [6]
* Formula for a 12.5–13.5-year old boy:
AS = 147.99 + 0.87 (stature, cm) – 0.77 (sitting height, cm) + 0.54 (triceps skinfold, mm) – 0.64 (subscapular skinfold, mm) – 3.39 (chronological age, year)
3) On the basis of mean parent stature [33]
* Formula for an 11-year old boy:
AS = 34.8579 + 0.736 (stature, cm) + 0.223 (mean parent stature, cm)
* Formula for a 6-year old girl:
AS = 38.9075 + 0.3718 (stature, cm) + 0.4856 (mean parent stature, cm)

3. The estimation of human physique or somatotype

Physique refers to an individual's body form, the configuration of the entire body or 'Gestalt', rather than specific features. The conceptual approach of William Sheldon to the assessment of physique, more known as the concept of the individual's *somatotype* is perhaps the approach most commonly used today [20]. An individ-

ual's somatotype is composed of three, more or less independent components: endomorphy, mesomorphy, and ectomorphy. *Endomorphy* is characterized by the predominance of the digestive organs, and by softness and roundness of contour throughout the body. Briefly, this component is simply seen as relative fatness. *Mesomorphy* is characterized by the predominance of muscle, bone, and connective tissues, so that muscles are prominent with sharp definition. *Ectomorphy* is characterized by linearity and fragility of build, with poor muscle development, and a predominance of surface area over body mass. The contribution of each component defines an individual's *somatotype* [20]. For assessing the somatotype in field conditions, today, the anthropometric Heath-Carter method is mostly used, in which the three components are determined by regression equations based on 10 anthropometric dimensions, relatively simply to measure [13, 24].

The applicability of the somatotype concept to sports is well-studied and well-documented, especially in Olympic athletes [e.g. 11, 13, 37, 59]. In general, from these studies it can be concluded that athletes of different sports are characterized by different somatotypes, and even differences in somatotype can be observed between athletes of different events or disciplines within a sport. These differences in morphological conformation are more accentuated relative to the level of competition. From the available literature, it can be said that the lack of a certain somatotype can be a limiting factor to reach an outstanding sports performance. In this context, Komadel's expression is of importance: "*Certain somatotypes may become limiting factors of performance in many sports. It is only in exceptional cases that individuals are able to compensate for an unfavourable somatotype with other excellent capabilities*" [33]. Up till now, there is no scientific evidence about the stability and prognostic value of the somatotype, and the obtained results are not equivocal [e.g. 13, 16, 28]. However, based on a longitudinal study in 82 boys, annually followed from 5 to 18 years of age, Walker and Tanner [62] came to the conclusion that "*Predictions of young-adult status were only modestly successful from age 5, but distinctly improved by age 8, showing correlations close to 0.8 for all variables except anthroposcopically rated endomor-*

phy" (p 220). This means that the adult somatotype can be predicted to a certain degree from the pre-pubescent period, pointing to some practical applicability of the use of the somatotype for the talent identification process. However, all the above mentioned longitudinal studies dealing with the stability of somatotypes are analyzed in non-athletic samples, and at our knowledge, no longitudinal studies investigating the predictability of the somatotype in highly talented youth are at hand. From cross-sectional studies, however, it can be concluded that young athletes have more or less similar somatotypes compared to the somatotypes observed in adult athletes of the same sport or event [12]. It can thus be said that a child's somatotype is a predisposal factor, besides several others, for future sports performance on an adult age. The estimation of a child's somatotype is a 'first' necessary item within the talent identification and talent selection process. However, extensive longitudinal studies on young talented children are necessary in order to clarify the prognostic value of the somatotype for each specific sport. It is of value that sport-specific training protocols has to be taken into account within the longitudinal study design in order to investigate the impact of the "sport-specific environment" on the genetically determined somatotype.

4. "Kinanthropometric profiling"

Every outstanding athlete, both at a young age and as a senior, has to be granted with many physical, physiological, and psychological qualities, otherwise he or she would not have reached the elite level. However, athletes also have some "weaknesses", which has to be known by the atletes themselves, and the coaches, the sports scientists, and sports physicians assisting them, in order to "improve" these weaknesses. One of the prime purposes of "Kinanthropometric profiling" is to *diagnose* these kind of weaknesses (within the kinanthropometric domain), so that the coach is allowed to set up certain training programmes in order to abolish these weaknesses.

Types of "profiling"

Two types of profiling should be carried out with high level athletes: (1) *General Profiling*, in which the talented child will be "profiled" against age- and sex-specific reference values obtained from a non-athletic representative sample of youngsters; (2) *Specific Profiling*, in which the talented athlete will be "compared" with sport-specific norms obtained from a representative sample of elite athletes of a specific sport or event. The *General Profiling* can be a useful vehicle for the identification of young talent, whereas the *Specific Profiling* is an indispensable instrument for the optimal guidance of the young athlete within the developmental process.

Parameters and tests used in "Kinanthropometric Profiling"

A complete "screening battery" has to contain tests and items of both the physical, physiological, psychological, and sports skill domain. Besides these aspects also health-related parameters have to be taken into account. For an overview of tests and items which were used in "profiling" batteries, reference is given to Bloomfield [7]. Most of these parameters are also necessary items within the talent identification and developmental process (see Table 1).

An overview of ***kinanthropometric*** parameters which can be included for "Kinanthropometric Profiling", depending on the purpose and/or the specific sport, is as follows:

* body mass and stature
  → *as "base-line" measurements*
* lenght-, breadth, and depth measurements
  → *as estimates of skeletal robustness*
* girth measurements
  → *as estimates of muscle development*
* skinfolds
  → *as estimates of fat development*
* somatotype
  → *as an estimate of whole body conformation*
* body composition
  → *as an estimate for fat mass and fat-free mass*

* proportional characteristics
  → *for the estimation of body level lenghts*
* basic motor abilities
  → *for the estimation of basic fitness condition*

The choice which items and/or tests has to be used in a certain "battery" depends on the kind of screening or profiling (general or specific), and is related to the specific sport or discipline. It is stressed that only tests and measurements has to be taken into account which are "specific" for a certain sport, i.e. all tests and measurements used must have a high degree of **"sports validity"**.

The construction of profile charts

"Profiling" is only possible if a sufficient amount of data are at hand of all the above mentioned items, tested and measured according to well-defined, standardized procedures [e.g. 20, 25, 36, 58]. It is also stressed that the data were gathered on a big amount of a representative sample of individuals (an athletic or a non-athletic population), varying in age and sex. The real "construction" of a profile chart is rather simple, and is based on some statistical techniques. Based on sex- and age-specific data, norms can be set up by means of percentile scores, T-scores, Z-scores, or as deviations from the mean, and this for each item separately. Profile charts as such are useful diagnostic tools in obtaining a quick view of a set of physical (or other) characteristics of a single subject, or if the mean is taken, as a group as a whole. The result in one measurement can easily be compared with those of other measurements. It has to be stressed that this "profiling" has to be relatively simple, so that all "steps" of the profiling process, and the training consequences which follow from this, can easily be understand by the athletes themselves.

Examples of kinanthropometric references and profiles

Several "reference" norms for non-athletic boys and girls aged 6 to 18 years for "General Profiling" are at hand; e.g. the *Eurofit Test Profiles* [34, 35]. This "Test battery" consists of nine motor items (Flamingo Balance, Plate Tapping, Sit & Reach, Standing Long Jump, Grip Strength, Sit Ups, Bent Arm Hang, Shuttle Run), one functional test (Endurance Shuttle Run), and seven body dimensions (body mass, stature, triceps, biceps, subscapular, supra-iliac, and medial calf skinfolds) [22]. Annual reference values for all items, expressed as "percentile scores", are at hand for 6 to 18 year old boys and girls [34, 35].

Sport-specific kinanthropometric reference values or norms, based on data gathered on a statistically sufficient amount of elite athletes, are relatively scare and/or not sufficiently worked-out. Herewith, we will give an overview of available normative anthropometric data, which can be used as **sport-specific "profile charts"** for some sports, gathered on both junior and/or senior elite athletes.

Anthropometric percentile scores for *"Olympic Athletes"* are at hand based on data gathered on 1265 athletes (1117 males and 148 females) competing at the 1968 Mexico City Olympic Games [15]. However, these "reference data" are not "sport-specific", because the data were gathered on athletes of 129 different kind of sports and/or disciplines. Extended *gymnastic-specific* anthropometric profile charts for elite male and female gymnasts are available. Data were gathered on 201 female and 165 male gymnasts during the 24th World Championships Artistic Gymnastics 1987, in Rotterdam, The Netherlands [17]. A *"Body Profile Analysis System"* to estimate the "ideal body size and shape" for both male and female *ballet dancers* and *gymnasts* is developed by Katch [30]. For the evaluation of *Brazilian volleyball and basketball players* an "detection model", based on Z-scores, was developed by Matsudo *et al.* [50]; and also "norms" for *Belgian male basketball players* [56] are at hand. Extended anthropometric reference data are at hand for *"aquatic sports"* (swimming, diving, water polo, synchronized swimming), based on data measured on

919 athletes at the World Championships Aquatic Sports, held in Perth, Australia, in 1991 [14]. A *multi-disciplinary* (anthropometric, basic-motor, and physiologic items) evaluation system for *swimmers* is worked out by Persyn and co-workers [52], in which *"style-specific"* profile charts for different swimming styles were developed [e.g. 21, 23, 61, 64]. Finally, anthropometric profile charts were recently composed for *male and female junior rowers.* An extended battery of 34 anthropometric dimensions were measured on 603 world class junior rowers (383 males and 220 females) during the FISA 1997 World Rowing Championships for Junior Rowers in Hazewinkel, Belgium [9]. Anthropometric Profile Charts, expressed as percentile scores, are available for the total group and for both rowing categories (sculling and sweeping) and this for the male and female rowers separately [19].

It is totally clear that the above mentioned list of normative or reference data is not exhaustive, and that for other sports and/or disciplines possibly some kind of "kinanthropometric norms" are at hand. However, in our opinion, a lot of research has to be done and there is a need for extended and multi-disciplinary cross-sectional studies on elite athletes in order to develop objective criteria which can be used in the talent detection and talent developmental process for a specific sport.

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

THE NUTRITIONAL STATUS OF 10- TO 12-YEAR-OLD BOLIVIAN GIRLS AND BOYS: THE RELATION BETWEEN ALTITUDE AND SOCIO ECONOMIC STATUS

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ABSTRACT

The nutrition of 229 native Bolivian schoolchildren 10–12 years old is described, 108 girls and boys living at the high altitude (HA) in La Paz (± 4000 m) and 121 girls and boys living at low altitude (LA) in St Cruz (± 400 m). A difference is made in girls (50) and boys (74) of low socio-economic status (LSES) and girls (54) and boys (41) of high socio-economic status (HSES). In the four years of study the dietary information was obtained with a 24-hours recall method, by interviewing the child and mother. The food-items are listed in household measures and weight if possible. All good items were converted into grams, and nutrients were calculated by using food composition tables of Latin America. The activities are measured by a 24-hours recall interview, covering the same 24 hours of the food intake interview. The results show, thet the nutritional intake is influenced by socio-economic status, but not by altitude. No significant sex difference are found in age, body weight, body height and fatmass. An altitude effect is demonstrated for body composition in girls; at low altitude the girls are not older but they are taller, heavier and fatter than their peers at high altitude.

Overall the energy and nutrient intake of HSES-girls and boys was significantly higher ($P < 0.01$) than the intake of the LSES-children, at both altitudes, no sex effect is demonstrated. HSES girls and boys consume greather amounts, especially more protein and fat, they are taller but also fatter. The physical activity of LSES children is higher than of the HSES girls and boys, at both altitudes. In comparision, the dietary intakes of the HSES-children seems too "rich",and of the LSES-children to some extent "poor". These results are reflected in smaller body height, and body weight of LSES-children, and higher fat mass in HSES-girls and boys irrespective of altitude.

Key words: Nutrition, Bolivia, schoolchildren, pre-pubertal, altitude, socio-economic status

INTRODUCTION

The physical development of schoolchildren is not automatically forseen to be healthy. Various enviromental conditions will influence the chance of a healthy growth and nutritional status of a child is also dependent of the wealth of the family in which the child grows up, especially in developing countries. In Latin-America, as well as in other developing countries all over the world, the concern applies especially those part of the population living in poverty. Children living under poor conditions will have more problems by achieving and maintaining growth and health, whereas their richer counterparts will have to face to a certain extent the "diseases of civilisation".

In countries, like Bolivia, not only the socio-econiomic status of the family is seen as a major factor affecting childhood growth, but also altitude can have its impact [3, 27, 28, 31]. The Andean population is born and raised at high altitude for centuries, but a part of the population in Bolivia is born and raised at low altitude. The growth pattern of any population is an end product of an interaction of many factors such as genetic background, nutritional status, disease, stress, hygenic situation and hypoxia at high altitude [1]. The fact that adolescents of poor nutritional status are sig-

nificantly shorter than their counterparts of good nutritional status indicates that under conditions of poor nutrition the role of genetic factors of growth can be overridden by the influence of environmental factors [6].

It is interesting to determine if altitude and socio-economic level are related to nutrition of prepubertal girls and boys, and if a lifestyle factor, such as nutrition may influence health factors such as growth.

In this article the results are shown of the nutritional intake, and the impact for growth and health, by comparing native highland and lowland Bolivian girls and boys, 10- to 12-year-old, living in urban La Paz and Santa Cruz de la Sierra.

SUBJECTS AND METHODS

The study was obtained to measure in four years pre-pubertal 10- to 12-year-old girls and boys living at high altitude (HA) and low altitude (LA), of high socio-economic status (HSES) and of low socio-economic status (LSES).

Subjects

The study included 114 girls and 115 boys ranging in age from 10- to 12-years (mostly derived from birth cerificates).

In La Paz, at ± 4000m (HA), a sample of 53 girls and 55 boys was examined in relation to nutrition; 26 girls and 17 boys of HSES, and 27 girls and 38 boys of LSES. In Santa Cruz de la Sierra, at ± 400m (LA), the dietary intake of a sample of 61 girls and 60 boys was studied; 38 girls and 24 boys of HSES and 23 girls and 36 boys of LSES.

Nutritional interview

In order to choose the valid method for determining the nutritional intake the following factors had to be considered:

- Each year during the months of July and August about four weeks were available to collect data (no seasonal variation), so a method was nessessary which lasts only a short time.
- One local nutritionist was present during the study period.
- The expected low variance in food items over the different weekdays.

Therefore the dietary information was obtained with a 24 hours recall method by interviewing the child. The mother, or the person who prepared dishes at home, was present to provide additional information about details of the meals and ingredients. All the interviews took place during home visits in the morning or in the afternoon, and lasted about 30 min. Commonly used utensils, such as plates, bowls and cups, were examined to estimate the quantities. Ingredients of meals were weighed if possible on a pair of scales (Figures 1a, 1b).

Figure 1a. The 24-h recell interview.

Figure 1b. Weighing ingredients during the dietary interview at home.

Activity interview

The activity profile was measured with a 24-hours recall method, covering the same 24-hours as the food intake. The activity data, collected by the interview in duration (minutes), were ranged in 4 different levels of intensities and converted to energy in kcalories: (a) sleep 0.8 kcal/min, (b) light activities (sitting, standing) 1.5 kcal/min, (c) medium activities (walking, cycling) 3.5 kcal/min and (d)heavy activities (running, carring loads) 7.0 kcal/min, based on standard conversions for children at age 10–12 years, and with a body weight of 30–35 kg [2].

Data analysis

The food intake was determined by converting household measures into grams and coding the food items separately. The nutrient composition was obtained primarly from the Bolivian table of food composition [19], supplemented for selected items from the INCAP table [14], and the SVEN table [29], and when no other

possibility was left a single item from the Dutch food composition table [22] was taken.

The data were analyzed in terms of nutrient composition and the adequacy was compared to daily allowances [4]. Energy and protein intakes are given in absolute values and per kg body weight per day.

To measure interactions between altitude (A), SES and sexes a two-way ANOVA is used, with significancy levels of $p \leq 0.05$ or $p \leq 0.01$ [23].

RESULTS

Anthropometrics

Table 1 and 2 present the age and the anthropometric characteristics of the groups of girls and boys. No differences are found between the sexes. The mean age of the girls and boys is 11.2 (± 0.05) years. The HA boys are significantly older ($P < 0.01$) than the LA boys. In girls the HSES groups are significantly older ($P < 0.01$) than their LSES counterparts. No other age differences are found.

Table 1. Mean and standard error (± SE) of the age and anthropometric characteristics of schoolgirls by altitude (A) and socio-economic status (SES)

GIRLS		HIGH ALTITUDE				LOW ALTITUDE				EFFECTS#		
		High SES (N = 26)		Low SES (N = 27)		High SES (N = 38)		Low SES (N = 23)		A	SES	AxSES
		mean	(se)	mean	(se)	mean	(se)	mean	(se)			
Age	yrs	11.4	(0.1)	10.8	(0.1)	11.4	(0.1)	11.0	(0.2)	NS	**	NS
Body weight	kg	35.1	(1.1)	29.6	(0.8)	42.8	(1.3)	30.7	(0.6)	**	**	**
Body height	cm	142.8	(1.3)	133.8	(1.2)	148.6	(0.9)	134.1	(1.2)	**	**	*
Skinfolds (sum of 4)	mm	41.6	(3.5)	32.8	(1.4)	54.6	(4.0)	34.1	(2.1)	*	**	NS

se = standard error of the mean.

= statistical difference: NS = non significant, * $P \leq 0.05$, ** $P \leq 0.01$.

Table 2. Mean and standard error (± SE) of the age and anthropometric characteristics of schoolboys by altitude (A) and socio-economic status (SES)

BOYS		HIGH ALTITUDE				LOW ALTITUDE				EFFECTS#		
		High SES (N = 17)		Low SES (N = 38)		High SES (N = 23)		Low SES (N = 36)		A	SES	AxSES
		mean	(se)	mean	(se)	mean	(se)	mean	(se)			
Age	yrs	11.5	(0.2)	11.4	(0.2)	10.9	(0.1)	11.0	(0.2)	**	NS	NS
Body weight	kg	40.7	(2.4)	31.7	(1.0)	38.9	(1.7)	31.5	(0.8)	NS	**	NS
Body height	cm	144.8	(1.6)	134.1	(1.3)	141.2	(1.3)	133.3	(1.2)	NS	**	NS
Skinfolds (sum of 4)	mm	53.8	(6.5)	28.8	(1.5)	52.8	(4.9)	33.6	(2.0)	NS	**	NS

se = standard error of the mean.

= statistical difference: NS = non significant, * $P \leq 0.05$, ** $P \leq 0.01$.

The anthropometric data indicate that HSES girls and boys are significantly taller, heavier and show a greather sum of four skinfolds than the LSES girls and boys. The mean height of the HSES girls is ± 146 cm, and of the LSES girls ± 134 cm; the mean weight is respectively ± 39.7 kg and ± 30.1 kg. The mean height of the HSES boys is ± 143 cm, and of the LSES boys 134 cm; the mean weight is respectively ± 39.7 kg and ± 31.6 kg. The mean sum of skinfolds of HSES girls is ± 49.3 mm, and of the LSES girls ± 33.4 mm; of HSES boys ± 53.2 mm, and of LSES boys ± 31.1 mm.

Table 3 shows that between the sexes no effects are demonstrated for these anthropometrics. There are significant interaction effects found of altitude and sexe (AxSEXE).

Table 3. The effects of altitude (A), socio-economic status (SES) and sexe on age and anthropometric characteristics of Bolivian boys (n = 115) and girls (n = 114)

		EFFECTS #						
		A	SES	SEXE	AxSES	AxSEXE	SESxSEXE	AxSESxSEXE
Age	yrs	NS	**	NS	NS	**	NS	NS
Body weight	kg	*	**	NS	NS	**	NS	
Body height	cm	NS	**	NS	NS	**	NS	
Skinfolds (sum of 4)	mm	*	**	NS	NS	NS	NS	NS

= statistical difference: NS = non significant, * $P \leq 0.05$, ** $P \leq 0.01$.

As shown in Table 1 girls show, besides the SES effect, significant effects of altitude for body weight; the girls at LA are heavier and taller ($P < 0.01$) and show also a significant higher sum of four skinfolds ($P < 0.05$).

Nutrient intake

The average daily energy and nutrient intake, as well as the energy output (kJ per kg body weight), are given in Table 4 for the girls and in Table 5 for the boys. The results show in general no differences between groups living at different altitudes, but significant differences between groups of high and low socio-economic status; the HSES schoolchildren have overall higher energy and nutrient intakes than their LSES counterparts. Almost all the nutrients are significantly ($P \leq 0.01$) higher in the HSES than in the LSES girls and boys, exept the energy intake per kg body weight and the carbohydrate intake. The results of the daily energy and nutrient intake show no significant differences between the two sexes (Table 6), with one exeption: Girls showed higher ascorbic acid intakes compared to their male counterparts, at both altitudes as well as both socio-economic status ($P < 0.05$).

The results of the two-way ANOVA (Table 6) indicate a significant interaction effect between altitude, socio-economic status and sexe for protein intake per kg body weight (/kg BW) ($P < 0.05$) and calcium intakes ($P \leq 0.01$). After separating the sexes, the interaction of A and SES is only found for girls in relation to the carbohydrate intake, whereas the boys show an interaction effect for protein/kgBW and calcium ($P < 0.05$). No other interaction effects could be demonstrated for the nutrient intake.

In Table 7 and 8 the contribution of the energy intake by protein, fat and carbohydrate are given. The differences between SES groups are statistical significant ($P \leq 0.01$). The nutrition of HSES girls and boys contributed higher percentages of energy from protein (ca. 15%) and fat (ca. 23%) compared to the LSES girls and boys (resp. ca. 12% and ca. 15%), but lower energy from carbohydrate (ca. 63% vs. ca. 74%), at both altitudes. An interaction

Table 4. Mean and standard error (± SE) of the nutrient intake and energy output of schoolgirls by altitude (A) and socio-economic status (SES)

GIRLS		HIGH ALTITUDE				LOW ALTITUDE				EFFECTS #		
		High SES (N = 26)		Low SES (N = 27)		High SES (N = 38)		Low SES (N = 23)		A	SES	AxSES
		mean	(se)	(mean	(se)	mean	(se)	mean	(se)			
Energy	MJ	9.9	(0.4)	8.4	(0.4)	11.4	(0.6)	8.7	(0.6)	NS	**	NS
Energy/kg BW	kJ	291	(18)	287	(15)	278	(19)	284	(21)	NS	NS	NS
Protein	g	93	(5.4)	56	(3.9)	100	(7.4)	63	(4.8)	NS	**	NS
Protein/kg BW	g	2.7	(0.2)	1.9	(0.1)	2.5	(0.2)	2.1	(0.2)	NS	**	NS
Fat	g	69	(5.7)	29	(3.9)	74	(7.1)	41	(5.6)	NS	**	NS
Carbohydrate	g	350	(16)	382	(16)	419	(20)	363	(26)	NS	NS	*
Calcium	mg	1504	(117)	714	(46)	1278	(119)	755	(95)	NS	**	NS
Thiamin	mg	1.1	(0.07)	0.66	(0.03)	0.89	(0.05)	0.65	(0.05)	NS	**	NS
Ascorbic Acid	mg	180	(29)	123	(23)	198	(28)	112	(24)	NS	*	NS
Activity Energy/kg BW		258	(9.4)	334	(13)	215	(6.0)	337	(12)	NS	**	*

se = standard error of the mean.

= statistical difference: NS = non significant, * $P \leq 0.05$, ** $P \leq 0.01$.

Table 5. Mean and standard error (± SE) of the nutrient intake and energy output of schoolboys by altitude (A) and socio-economic status (SES)

BOYS		HIGH ALTITUDE				LOW ALTITUDE				EFFECTS #		
		High SES (N=17)		Low SES (N=38)		High SES (N=24)		Low SES (N=36)		A	SES	AxSES
		mean	(se)	(mean	(se)	mean	(se)	mean	(se)			
Energy	MJ	9.8	(0.7)	8.3	(0.4)	10.7	(0.6)	7.8	(0.3)	NS	**	NS
Energy/kg BW	kJ	250	(21)	268	(13)	284	(21)	254	(10)	NS	NS	NS
Protein	g	85	(7.8)	60	(4.1)	100	(8.2)	53	(2.9)	NS	**	NS
Protein/kg BW	g	2.1	(0.2)	1.9	(0.1)	2.6	(0.2)	1.7	(0.1)	NS	**	*
Fat	g	62	(7.4)	37	(4.3)	67	(5.8)	30	(2.8)	NS	**	NS
Carbohydrate	g	370	(26)	353	(13)	395	(23)	352	(12)	NS	NS	NS
Calcium	mg	1315	(140)	958	(68)	1596	(178)	716	(57)	NS	**	*
Thiamin	mg	0.89	(0.08)	0.66	(0.05)	0.84	(0.06)	0.61	(0.03)	NS	**	NS
Ascorbic Acid	mg	170	(46)	72	(11)	135	(20)	80	(12)	NS	*	NS
Activity Energy/kg BW		223	(10)	332	(13)	248	(12)	367	(15)	*	**	NS

se = standard error of the mean.

= statistical difference: NS = non significant, * $P \leq 0.05$, ** $P \leq 0.01$.

Table 6. The effects of altitude (A), socio-economic status (SES) and sexe on the energy and nutrient intake, energy output of Bolivian boys (n = 115) and girls (n = 114)

		EFFECTS #						
		A	SES	SEXE	AxSES	AxSEXE	SESxSEXE	AxSESxSEXE
Energy	MJ	NS	**	NS	NS	NS	NS	NS
Energy/kg BW	kJ	NS	NS	NS	NS	NS	NS	NS
Protein	g	NS	**	NS	NS	NS	NS	NS
Protein/kg BW	g	NS	**	NS	NS	NS	*	NS
Fat	g	NS	**	NS	NS	NS	NS	NS
Carbohydrate	g	NS	NS	NS	*	NS	NS	NS
Calcium	mg	NS	**	NS	NS	NS	**	NS
Thiamin	mg	*	**	NS	NS	NS	NS	NS
Ascorbic Acid	mg	NS	**	*	NS	NS	NS	NS
Activity Energy/kg BW	kJ	NS	**	NS	NS	**	NS	NS

= statistical difference: NS = non significant, * $P \leq 0.05$, ** $P \leq 0.01$.

effect between altitude and socio-economic status is only found in girls for the percentage energy from all the macronutrients (Table 7).

Table 7. Mean and standard error (± SE) of the macronutrient intake as a percentage of the energy intake of schoolgirls by altitude (A) and socio-economic status (SES)

GIRLS		HIGH ALTITUDE				LOW ALTITUDE				EFFECTS #		
		High SES (N = 26)		Low SES (N = 27)		High SES (N = 38)		Low SES (N = 23)		A	SES	AxSES
		mean	(se)	mean	(se)	mean	(se)	mean	(se)			
Protein	En%	15.8	(0.6)	11.0	(0.4)	14.5	(0.5)	12.4	(0.5)	NS	**	**
Fat	En%	25.8	(1.6)	12.6	(1.1)	23.1	(1.2)	17.2	(1.7)	NS	**	*
Carbo-hydrate	En%	60.0	(1.8)	77.2	(1.4)	63.2	(1.6)	70.6	(1.8)	NS	**	**

se = standard error of the mean.

= statistical difference: NS = non significant, * $P \leq 0.05$, ** $P \leq 0.01$.

Table 8. Mean and standard error (± SE) of the macronutrient intake as a percentage of the energy intake of schoolboys by altitude (A) and socio-economic status (SES)

BOYS		HIGH ALTITUDE				LOW ALTITUDE				EFFECTS #		
		High SES (N = 26)		Low SES (N = 27)		High SES (N = 38)		Low SES (N = 23)		A	SES	AxSES
		mean	(se)	mean	(se)	mean	(se)	mean	(se)			
Protein	En%	14.4	(0.8)	11.9	(0.4)	15.3	(0.5)	11.3	(0.4)	NS	**	NS
Fat	En%	23.1	(1.7)	15.9	(1.2)	23.2	(1.3)	13.9	(1.0)	NS	**	NS
Carbo-hydrate	En%	64.0	(2.0)	72.7	(1.3)	62.4	(1.5)	75.5	(1.1)	NS	**	NS

se = standard error of the mean.

= statistical difference: NS = non significant, * $P \leq 0.05$, ** $P \leq 0.01$.

Daily physical activity

The data of the activity interview, calculated as energy per kg body weight (Table 6), showed no difference between boys and girls, but a significantly ($P \leq 0.01$) higher activity level of LSES girls and

boys compared to their HSES counterparts (Table 4 and 5). Also an effect of altitude could be demonstrated; boys at low altitude were significantly ($P \leq 0.05$) more active than their peers at high altitude; in HSES girls the opposite is found, they are more active at high altitude than their HSES peers at low altitude. The LSES girls at both altitudes had the same level of activity energy per kg body weight.

DISCUSSION

Dietary measurement method

In this study a 24-hours dietary recall was used to estimate the daily food intake. Garn *et al.* [7] describe that a single-day dietary survey tends to overestimate levels of nutritional deficiency, or underestimate the daily variation, because they fail to account for intra-individual variation in intakes. Indeed, it is well known that in western countries there will be a large day-to-day difference. However, in a developing country like Bolivia it has been demonstrated in poor families that there is much less variability in meal patterns and possibilities for food choices [20] than in rich (Western) diets.

Another possible interfering factor in the food intake could be the seasonal variation, especially in poor families. Leonard and Thomas [17] described seasonal differences of 15% to 20% of the daily energy intake, namely because of the pre- and postharvest availability of locally produced foods in Peru. Leonard [18] indicated that the availability is highest between June and August in the Nuñoa highlands, in southern Peru next to Bolivia. Our study took place all four years in the months of July and August.

So for the purpose of this study within the limitations of the field conditions a 24-hour recall was seen to be a suitable and preferable method.

Dietary quality

The meal pattern of the schoolchildren , at both altitudes, was relatively homogenous. Most children repoted a breakfast of a roll and a warm beverage, usually tea or coffee sweeted with sugar. HSES girls and boys more frequently reported the use of a milk product, and the use of butter, margarine or other spreads. During school time most children consumed a light snack, such as gelatin, bread and other sweets. At lunch time usually the largest meal was eaten, commonly a soup with meat or chicken and vegetables. In the more wealthy families a *segundo* was also served, consisting of meat, chicken, egg and potato (in La Paz more often *chuño*) or rice. During the afternoon the girls and boys reported mostly a tea break with a sweetened beverage and bread. If a late evening meal was consumed it consisted of a soup, mostly leftovers from previous meals, or both.

Evaluation of the quality of the diet of the schoolchildren showed overall levels of energy and nutrient intake relatively high in the HSES groups and low in the LSES groups. This is reflected in the body composition (Table 1 and 2); HSES girls and boys have a relative high body weight in relation to their body height, whereas LSES girls and boys were relatively small in relation to their age (see Figure 2a, b, and 3a, b) [11]. The sum of four skinfolds indicates the same direction, HSES children showed significant higher mean values than LSES children.

The FAO/WHO committees [4] recommend a daily energy intake of 8.2 MJ in 10- to 12-year-old girls and 9.2 MJ in 10- to 12-year-old boys. Recommendations for the energy requirements of children are based mainly on measurements of the actual food intake of healthy children with a normal growth pattern. In this study the HSES girls and boys showed a higher energy intake (± 10 to 11 MJ per day), whereas the LSES girls showed an intake comparable to the recommendations (± 8.5 MJ per day).

Obviously the energy intake of children must allow for satisfactory growth and physical development, and for the high degree of activity that is characteristic in healthy children [2]. Tanner [30] pointed out that the first thing that happens in the undernourished

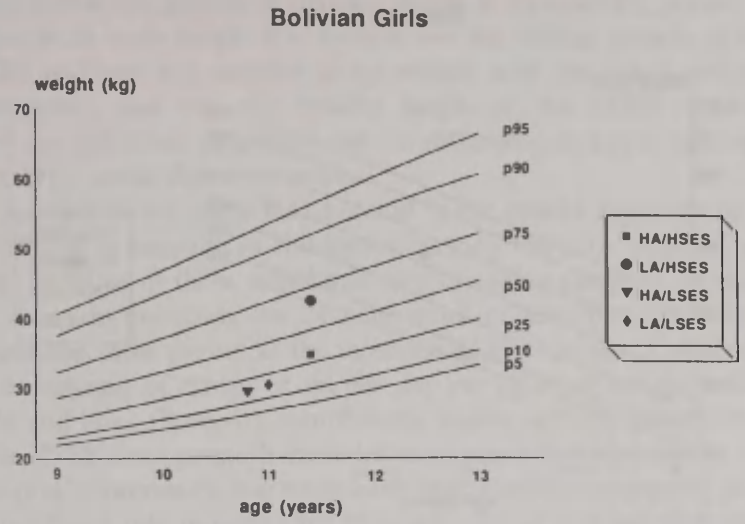

Figure 2a. The body weight of 10–12-year-old Bolivian girls plotted against the NCHS-percentiles for weight [11].

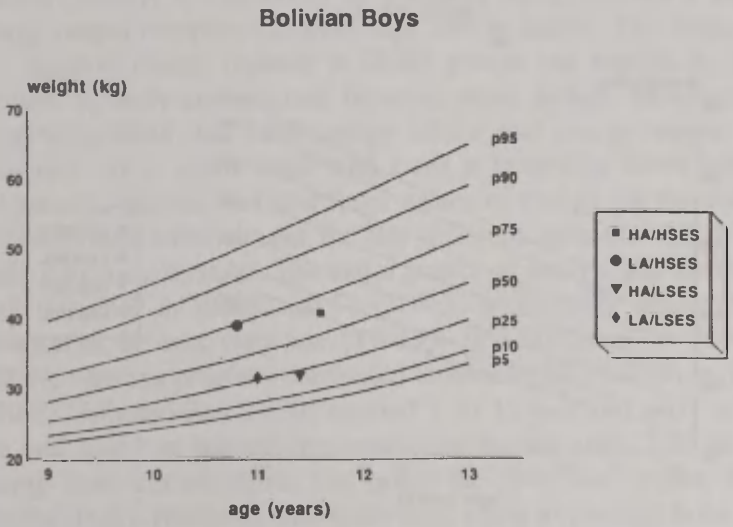

Figure 2b. The body weight of 10–12-year-old Bolivian boys plotted against the NCHS-percentiles for weight [11].

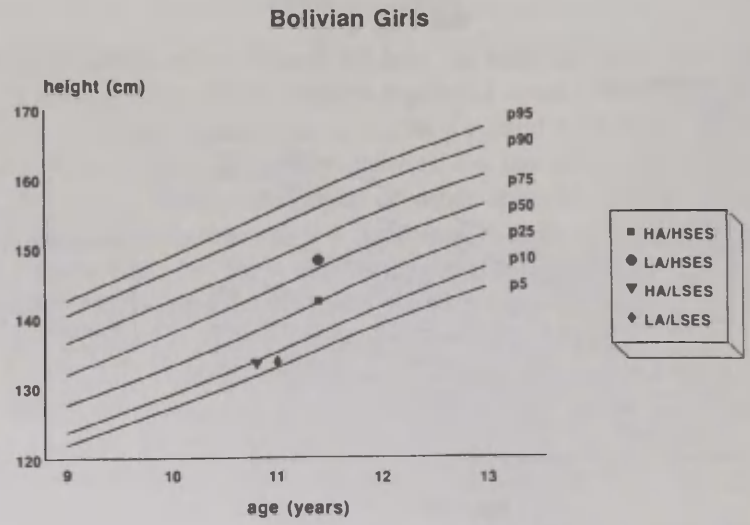

Figure 3a. The body height of 10–12-year-old Bolivian girls plotted against the NCHS-percentiles for weight [11].

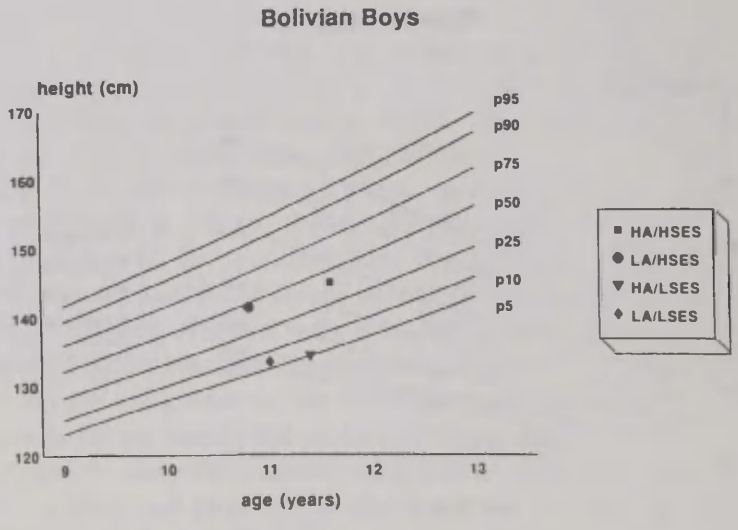

Figure 3b. The body height of 10–12-year-old Bolivian boys plotted against the NCHS-percentiles for weight [11].

child is that the growth is slowing down. If satisfactory growth is reflected in body height it is evident that the energy intakes of the HSES children was anyway in agreement with the mentioned requirements, and that the smaller height of the LSES children (4–9 cm difference in girls, 8–10 cm difference in boys) indicates an energy intake that was too low.

Another factor taken into account is the energy expenditure. It is difficult to measure in children accurately the daily physical activity because of their varied and ever changing range of physical activities. In our study the 24-hour recall of activities (interview) covers the same period as the interviewed food intake. Calculated as the amount of energy spent per day per kg body weight, LSES girls and boys showed a significantly higher activity pattern than their HSES sexe peers. It must be recognized that children in developing countries of low socio-economic families commonly play a significant role in caring for lifestock, and in looking after their younger brothers and sisters [17]. Energy should be available for these essential tasks. The LSES girls and boys in our study showed an energy expenditure higher than energy intake, while the HSES children, mostly not involved in houshold tasks, showed a lower energy output compared to their high energy intake. The tendency to a negative energy balance in HSES groups can explain the differences in body composition between these groups. However, it must be stressed that both energy intake and energy output are measured on a recall basis and over a relatively short period (24 hours). Also the fact that fixed values of energy for the different intensities were chosen for the different activities has to be taken into consideration. The major source of energy was carbohydrate (60–64% in HSES, and 71–77% in LSES). The energy contribution of fat was very low (13–17% in LSES, and 23–26% in HSES), whereas protein contributed to about 11% (LSES) to 16% (HSES). Moreno-Black [20] studied 7 to 11 year old boys in La Paz and found in general the same contribution with 77% of the energy from carbohydrate, but lower fat (8%) and higher from protein (15%). However, that study took place in younger boys and during the period of October to November. So the differences may

be partly due to seasonal variation, as well as to the different age of the children.

Dietary quality and altitude

Although people who are suddenly exposed to high altitudes suffer anorexia, weight loss and reduction in aerobic capacity, these are temporary effects that disappear with acclimatization. Greksa *et al.* [9, 10] found that hypoxia and /or the colds as the principle stressors may actually have a significant impact on statural growth. At high altitude the slowed rate of statural growth and a smaller body size of Andean children have generally been viewed as adaptive responses with the role of nutrition as negligeable or secondary [8]. Freyre and Ortiz [5] found at sea level as well as at an altitude of 3400 m in 10/11 year-old boys of middle to high socio-economic class a height of ± 138 to 141 cm. In our study the mean height of about 141 cm was found at LA for HSES boys, but at HA the HSES were even taller. However, we have to consider that the HSES boys at HA were sigificantly older than the HSES boys at LA. In the mentioned study [6], 10/11 year-old girls at sea level showed a height of 138 to 144 cm, and at 3400 m altitude of 136 to 142 cm. The LA girls in our study are taller than the HA peers, especially the HSES girls. However, in the Stinson study [28] 10- to 11 year-old Aymara children living at high altitude in Bolivia showed even a smaller height in boys (± 132 cm) and in girls (± 127 cm) compared to the youngsters at high altitude in our study.

In our study a significant interaction effect of altitude and socio-economic status was observed only in the girls, at LA the HSES and the LSES girls are taller and heavier in comparision to their HA peers (Table 1). Haas *et al.* [12] found 25% more adipose tissue in La Paz (HA) than in Santa Cruz (LA) in small infants (age 6 to 12 months). We found significant differences in the sum of four skinfolds only in girls ($p < 0.05$), LA girls (both SES groups) showed a higher sum of skinfolds compared to the HA peers, but no interaction effect could be demonstrated. A sig-

nificant age effect is found for boys, HA boys are older than LA boys ($P < 0.01$).

The differences in nutritional intakes were not statistically significant between HA and LA groups. However, at high altitude HSES-girls are significantly smaller (6 cm) and lighter (8 kg) than their peers at low altitude, although the calender age is the same. Therefore the differences may be explained by differences in pubertal stages.

Thus, there is no evidence that the requirements for energy and protein are altered in those who habitually live at high altitudes. The higher activity pattern in children at LA compared to HA, especially in boys, may be explained by other enviromental differences, such as low temperature and living on mountain slopes.

Our findings suggest that altitude does not seem to affect to a great extent the nutritional intake. Only significant interaction effects of altitude, with socio-economic status and sexe are found for the protein and calcium intake (Table 6).

Dietary quality and socio-economic status

The girls and boys of the HSES families showed a dietary intake with higher energy and nutrient values than the food intake of their peers with LSES. This is highly statistically significant ($P < 0.01$) (Table 1 and 2), and is reflected in the body composition (Table 5 and 6). The LSES girls are on the average 9 to 14 cm shorter, and the LSES boys on the average about 7 cm shorter than their age related counterparts. The height in HSES boys indicates a normal growth rate for their age. Spurr *et al.* [24] found for 10- to 12-year-old normal healthy Columbian girls a height of 140 cm and of normal boys of 138 cm, but undernourished counterparts showed a mean height of 134 cm for both sexes. The LSES girls and boys in our study showed the same mean height of 134 cm. Although the ethnic background in the study of Spurr *et al.* [25] was different (± 80% mestizo ancestry) from our LSES population, they found it justified to use the values obtained from school children from upper socio-economic groups as standards. In our study it is ques-

tionable to use HSES children as standards, because they are not only heavier than Columbian age-peers (girls 2–10 kg, boys 6–8 kg) but show also a higher sum of skinfolds. Compared to NCHS-growth percentiles norms [11] the HSES children in our study are spread around the 50th percentile for height by age, but the LSES girls and boys are found to be small for their age and grouped around the 5th percentile (Figure 3a, 3b). Maybe, only on the basis of body height the conclusion could be drawn that our LSES children are nutritionally deprived. The HSES girls and boys in the Stinson growth study in La Paz [27] showed also a height of about 141 cm at the age of 11 years. In terms of body weight: Freye and Ortiz [5] found a weight of about 35/37 kg for HSES girls, and 34/36 kg for HSES boys; Stinson indicated about 33 kg in both sexes. The HSES girls and boys in our study showed a higher body weight (35 to 40 kg), whereas LSES girls and boys weighed only 30 to 32 kg although, a significant SES effect in girls (HSES girls are older than LSES girls, $p < 0.01$), it might be that the taller and heavier body composition is partially due to the onset of puberty, especially in girls. In western societies it is well known that puberty starts in girls at an earlier age than in boys [16]. Himes *et al.* [13] described rural Guatemalan youth and young adults and showed starting puberty by means of serum alkaline phosphatase. Girls showed a rapid decline at the chronological age of 11 years, and boys at 14 year-old.

The greather of our sum of four skinfolds of the HSES schoolchildren, as an estimation of body fat, indicates that these girls and boys had a more than adequate energy intake. This result is also reflected in the lower activity pattern of these HSES youngsters. The situation in LSES schoolchildren shows a somewhat low energy intake, although the sum of four skinfolds of about 30 mm in these kids does not indicate a serious energy deficiency, the body height (around the 5th percentile) does presume a growth retardation. Given the socio-economic status in the HSES girls and boys it was assumed that the better nourished children were healthier than the peers of lower SES, but this assumption does not seem to be realistic. According to athropometric data the HSES groups show a tendency toward becoming overweight, partly due to inactivity.

which might affect their health as is found in the rich parts of the world.

CONCLUSION

This study demonstrates that in 10- to 12-year -old Bolivian schoolchildren the nutritional intake is influenced by socio-economic status, but not by altitude. No significant sex differences are found in age, body height, weight and fat mass. An altitude effect is found for body composition in girls; although the girls at low altitude are not significantly older they are taller, heavier and fatter than their peers at high altitude. This effect is mainly demonstrated by high socio-economic girls, and might be a puberty effect. Improvement of living conditions is thought to cause a secular trend toward greather stature and body weight for low socio-economic status children. High socio-economic status girls and boys consume greather amounts, especially more protein and fat, they are taller, but also fatter. LSES children consume less energy than their HSES peers, and this energy is mostly contributed by carbohydrates. While the total contribution of protein in LSES girls and boys (± 11.5%) does not seem too low, a possible mal-absorption cannot be excluded [15]. The physical activity of LSES children was higher than of the HSES girls and boys, thus their life style seems to be healthier compared to the HSES children.

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

LACK OF ESTROGENIC EFFECT ON TETANIC CONTRACTILE PARAMETERS OF SOLEUS MUSCLE IN MALE AND FEMALE MICE

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ABSTRACT

Previous human studies on the effects of estrogen on skeletal muscle force and fatigue rates have been contradictory. This study investigated the effects of estrogen on *in vitro* tetanic contractile parameters of mouse soleus muscle. Adult male and female C57-BL mice were injected with 10μg β-estradiol 3-benzoate/0.1 ml olive oil·100 g body weight^{-1} or injected with vehicle alone daily for 14 days. Isolated soleus muscles were studied during *in vitro* fatiguing tetanic contractions and recovery. Measurements of peak isometric tension during a tetanus (P_o), and maximal rate of tetanic force development ($+dF/dt_{max}$) were determined throughout the 50 min fatigue and recovery protocol. No significant differences between gender or between estrogen and sham injected animals were found in pre-fatigue Po or $+dF/dt_{max}$. As well, no significant differences in Po or $+dF/dt_{max}$ existed between estrogen or sham injected males or females at any point in the fatigue or recovery period. This suggests that if estrogen does affect soleus muscle function, this may not occur through direct influence on the muscle itself.

Key words: estrogen, muscle, fatigue, gender

INTRODUCTION

Recently several conflicting reports have emerged regarding the possible effects of estrogen on muscle strength, fatiguability and post-exercise strength recovery in human females. Phillips *et al.* [9] reported that estrogen replacement therapy diminished strength loss in post-menopause females. Sarwar *et al.* [11] found improved force generation and reduced fatiguability for voluntary and electrically stimulated quadriceps and forearm muscles in young adult females during phases of the menstrual cycle corresponding to higher circulating levels of estrogen. Recently Skelton *et al.* [13] concluded a longitudinal study which found estrogen replacement therapy to increase voluntary adductor pollicis strength in women who were post-menopausal for 5–15 years. In addition, Reis *et al.* [10] have suggested that weight training which is emphasized in the follicular phase of the menstrual cycle when estrogen, and possibly other hormones are relatively higher may enhance strength gains in young women.

In contrast, others have found little effect of oral contraceptives on exercise performance [3] or variation in maximal voluntary muscle force or exercise performance in young females throughout the menstrual cycle [2, 7]. In another study, no difference in muscle function was reported in estrogen treated or control post-menopause females [14]. Greeves *et al.* [5] also found no effect of estrogen on strength or fatiguability of the first dorsal interosseus muscle in females exposed to supra-physiological estrogen levels during *in vitro* fertilization.

The potential for an estrogenic effect on muscle function is of interest for its possible positive effects on physical functioning capacity of post-menopausal females optimize as well as sports performance in all females. However its actual efficacy and potential mechanisms of action on skeletal muscle have not yet been firmly established. Previous studies have reported that estrogen may affect skeletal muscle fuel utilization during exercise [6], and diminish exercise induced muscle damage due possibly to its antioxidant properties [1, 15]. Estrogen has also been reported to affect the function and contractility of smooth and cardiac muscle [4, 12].

Since many factors may affect human muscle force generation *in vivo*, this experiment attempted to isolate the effects of estrogen on tetanic contractile characteristics in soleus muscle using an *in vitro* mouse muscle model. The present study investigated the effects of supra-physiological estrogen levels on tetanic contractile properties and force generation during fatiguing exercise and recovery. It is possible that prior estrogen exposure may alter skeletal muscle sensitivity to subsequent estrogen administration. Hence sexually mature male and female animals were employed to attempt to discern if prior estrogen exposure could influence soleus muscle function when exposed to supra-normal estrogen levels. Since estrogen has the potential to mitigate oxidative stress and to reduce muscle glycogen utilization during exercise, it was hypothesized that estrogen administration would diminish soleus muscle fatigue and facilitate its recovery in the experimental model employed.

MATERIAL AND METHODS

Pretreatment with Estrogen

The University of Waterloo Committee on Animal Care found the methods employed in this study to be in accordance with the principles and guidelines of the Canadian Council on Animal Care. Male and female 5–6 week old C57-BL mice were obtained from Harlan Sprague Dawley, Indianapolis, IN and maintained on a 12:12 hour reverse light:dark cycle. Mice of the same gender were housed in groups of two or three in standard shoebox cages. Cages were lined with beta-chip bedding and enriched with ABS pipe and shredded paper. PMI rodent lab chow 5001 (PMI Feeds, Inc., St. Louis, MO) and water were provided *ad libitum*.

At the age of 7–8 weeks, mice were given subcutaneous injections for fourteen consecutive days. Sham injections consisted of virgin olive oil alone. Estrogen injections consisted of β-estradiol 3-benzoate (estrogen) in virgin olive oil (Sigma Diagnostics,

St. Louis, MO). Forty eight animals were randomly assigned to each of 4 experimental groups (12 per group): Sham Females and Sham Males both received 0.1 ml olive oil·100 g body weight^{-1}, while Estrogen Females and Estrogen Males both received 10 μg estrogen/0.1 ml olive oil·100 g body weight^{-1}. This level of estrogen administration has been previously demonstrated to induce significant metabolic changes in rats [6]. Mice were weighed weekly and injected dosages modified to changes in body weight.

Muscle Preparation

Mice were anaesthetized with sodium pentobarbital (80 mg/kg body weight intraperitoneal) approximately 24 hours after receiving the last experimental injection and the soleus muscle, surgically removed. Removed muscles were suspended in a jacketed muscle bath (Radnotti Glass, Monrovia, CA) containing oxygenated Ringers solution (95% O_2, 5% CO_2) maintained at 25°C. The Ringers solution contained 118 mM NaCl, 1.2 mM KH_2PO_4, 1.2 mM $MgSO_4$, 1.9 mM $CaCl_2$, 11 mM glucose, and 25 mM $NaHCO_3$. The muscle was suspended vertically by securing the proximal tendon in a plexiglass clamp located at the base of the bath and the distal tendon was tied with suture and attached to the arm of a servomotor (Cambridge Technologies, model 300H Dual Mode Servo) that provided force output. Animals were subsequently killed after drawing blood from the heart.

Isolated mouse soleus muscles were maintained at 25°C and subjected to an experimental protocol proceeding a 30 minute equilibration period, determination of optimal muscle length for isometric twitch force development (L_o), and a further 12 minutes of recovery. The fatigue protocol consisted of trains of pulses delivered once per second at a frequency of 150 Hz and duration of 400 ms. SOL muscles were stimulated for 20 minutes, also using trains of pulses at the same frequency and duration. This protocol has been used previously in our laboratory to elicit fatigue [16]. Following the recovery period, muscles were removed from the

muscle bath and plexiglass clamp, excess tendon was removed, and then muscles were blotted and weighed.

Contractile Data

Stimulation was applied by a Grass S-48 stimulator (Grass Instruments, Quincy, MA) via closely flanking platinum wire electrodes. A supra-maximal stimulation voltage was used (60 V) with a pulse duration of 0.2 ms. Force data were collected on-line at 1000 Hz and immediately analysed by "Twitch" software (J. Pezzack, University of Waterloo) for parameters described below. One force curve was analyzed at each time point.

Parameters of interest for tetanic mechanical force development included resting tension, peak isometric tension during a tetanus (P_o, mN), and maximal rate of tetanic force development ($+dF/dt_{max}$, $mN \cdot ms^{-1}$). The P_o and $+dF/dt_{max}$ for soleus muscles were collected at rest (time = 0), during the 20 minute stimulation period (0.25, 0.5, 1, 1.5, 3, 5, 10, 15, 19.5 min) and throughout a 30 minute recovery period (20.5, 21, 23, 25, 30, 35, 40, 45, and 50 minutes). All values were expressed as a percentage of the initial value (collected at time = 0) and referred to as relative change.

Blood Analysis

After the removal of muscles, blood was drawn by cardiac puncture to the left ventricle. Blood was transferred to a centrifuge tube and placed on ice for 12 minutes. Tubes were rimmed and any clots removed before spinning in a refrigerated centrifuge at 9000xg for 15 minutes. Serum was pipetted into an empty centrifuge tube and stored at –80°C until analysis. Serum estradiol content was determined via a commercially prepared double antibody radioimmunoassay (RIA) kit (Diagnostic Products Corporation, Los Angeles, CA).

Statistical Analysis

Data was analyzed using a two way repeated measures analysis of variance (ANOVA). Significance was set at $p < 0.05$. A difference between groups would be indicated if a difference existed at any of the experimental time points.

RESULTS

Mice in all experimental groups were of similar age (mean = 67 days at conclusion of the experiment). At time of sacrifice, there were no significant differences in body weight between female sham (21.5 ± 2.1 g) or estrogen (23.5 ± 1.7 g) mice. However, estrogen injected males weighed significantly more (25.8 ± 1.6 g) than sham injected males (21.5 ± 2.2 g). Soleus muscle mass was not significantly different between any of the groups; female sham (8.6 ± 1.7 mg), female estrogen (9.2 ± 1.7 mg), male sham (9.9 ± 0.5 mg), male estrogen (11.9 ± 2.5 mg).

To verify the efficacy of 14 days of injections, serum estradiol levels were measured from each experimental group at time of sacrifice. Serum estradiol values are presented in Table 1. Sham injected females had significantly ($p < 0.05$) higher serum estadiol levels than sham injected males. Both estradiol injected males and females had significantly ($p < 0.01$) higher serum estradiol levels than their sham injected counterparts, with estradiol injected females also being higher than estardiol injected males ($p < 0.05$).

Table 1. Serum estradiol concentrations of experimental groups as determined by radioimmunoassay

Group (n)	Serum Estradiol ($pg \cdot ml^{-1}$)
Female Sham (12)	23.9 ± 15.7
Female Estrogen (9)	88.3 ± 16.9*
Male Sham (10)	8.0 ± 3.5
Male Estrogen (12)	38.5 ± 8.2*

Values are mean ± S.D., *Significantly ($p < 0.05$) greater than same gender sham group.

Tetanic Contractile Parameters for soleus muscles

Soleus muscle tetanic force (Po) data, as a percentage of pre-fatigue Po, during the fatigue protocol and recovery is depicted in Figure 1. Pre-fatigue soleus Po (mN) was similar between groups; female sham (172.8 ± 33.3), female estrogen (179.0 ± 18.9), male sham (177.0 ± 28.2), male estrogen (180.1 ± 26.8). Po was rapidly reduced and dropped to a plateau within the first 5 min of the fatigue protocol for all groups. There was little further change in Po for the remaining 15 min of the fatigue protocol. However, Po rapidly returned to initial levels within the first 5 min of recovery with little further change for the remainder of the recovery period. There were no significant within-gender differences in Po between estrogen or sham injected groups during the fatigue or recovery time-course. As well, there no significant between gender differences in Po. The resting specific tension of soleus muscles were also recorded prior to tetanic contractions. There were no differences in soleus resting tension between groups at any time point.

Soleus muscle maximal rate of tetanic force development ($+dF/dt_{max}$) data, as a percentage of pre-fatigue $+dF/dt_{max}$ is depicted in Figure 2. As with Po, pre-fatigue soleus $+dF/dt_{max}$ ($mN \cdot ms^{-1}$) was similar between groups; female sham (2.4 ± 0.5), female estrogen (2.8 ± 0.3), male sham (2.9 ± 0.3), male estrogen (2.6 ± 0.7). $+dF/dt_{max}$ changed in a similar manner to changes in Po throughout the fatigue and recovery protocol, with an initial rapid drop followed by a plateau during the fatigue protocol and a rapid return to pre-fatigue values during the recovery period. No significant differences between gender differences were noted. In addition, there was no significant within-gender effect of estrogen injection on $+dF/dt_{max}$ at any point in the fatigue-recovery period.

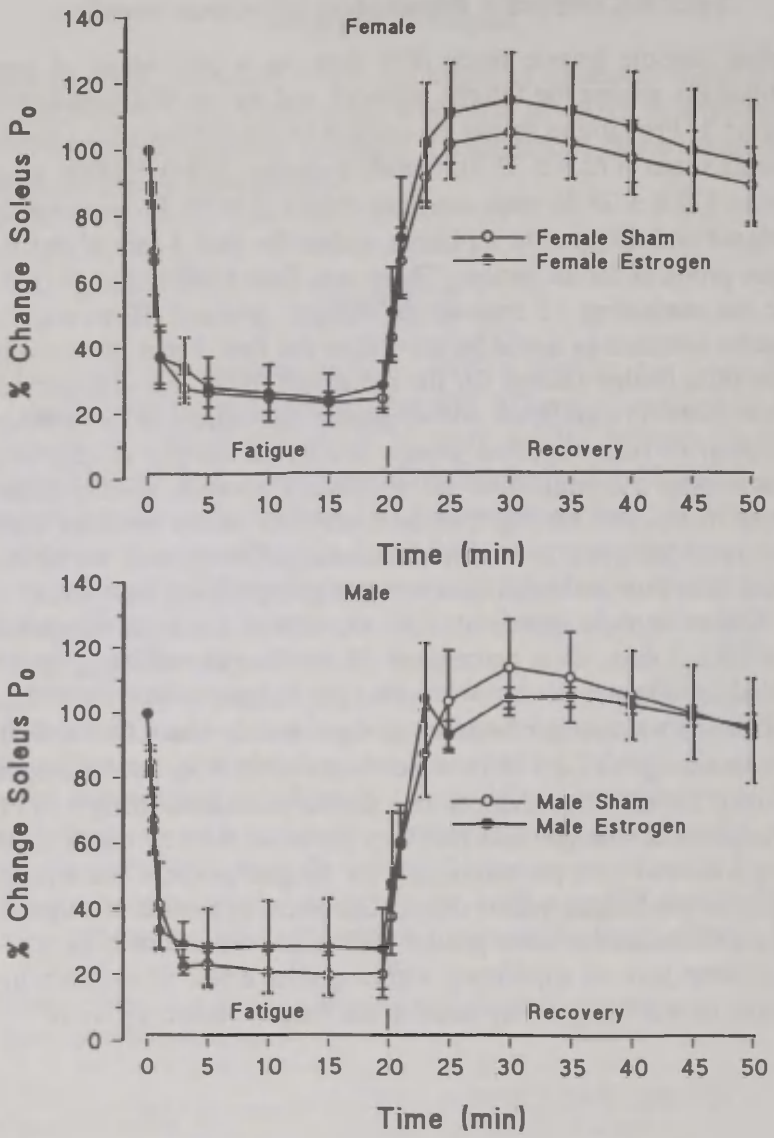

Figure 1. Change in Soleus muscle Po in female and male rats during fatiguing *in vitro* contractions and recovery.
(n = 12), Mean ± S.D., No significant difference between groups ($p > 0.05$).

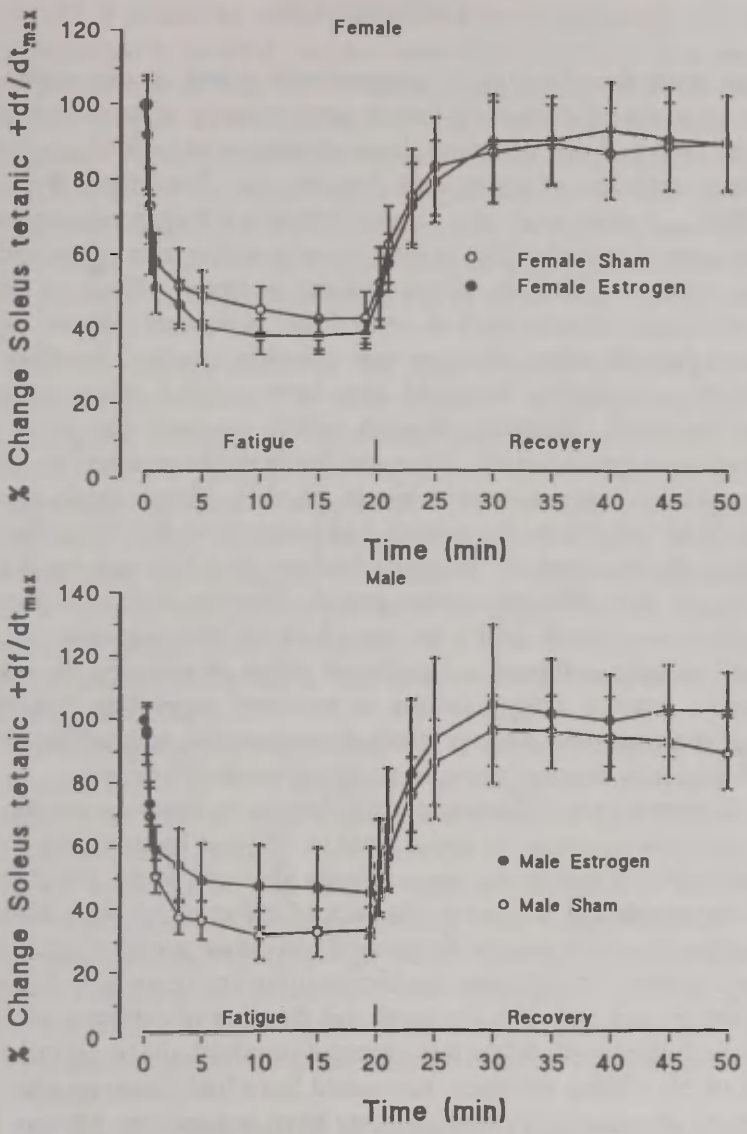

Figure 2. Change in Soleus muscle $+dF/dt_{max}$ in female and male rats during fatiguing *in vitro* contractions and recovery.
(n = 12), Mean ± S.D., No significant difference between groups ($p > 0.05$).

DISCUSSION

This study found a lack of demonstrable effect of two weeks of estrogen administration on fatigue and recovery of *in vitro* tetanic force (Po) and rate of tetanic force development ($+dF/dt_{max}$) in the soleus muscles of male and female rats. Pre-fatigue Po and $+dF/dt_{max}$ values were also similar between estrogen administered and control animals. The *in vitro* muscle preparation employed in this study would have eliminated the potential effects of other physiological factors such as central and peripheral nervous influences through which estrogen may possibly manifest its effect on muscle contractility. It would also have negated other potential psychological influences through which estrogen may have affected changes in muscle force and fatiguability reported by other researchers using human subjects [9, 11]. Hence these results would be specific to the potential of estrogen to directly influence soleus function and the negative findings therefore suggest that if estrogen does influence soleus muscle function it may not be via mechanisms found within the muscle itself. Neither male nor female animals exhibited a significant effect of estrogen on soleus muscle function during fatigue or recovery suggesting that prior estrogen exposure, had no effect on soleus muscle function when subsequently exposed to supra-maximal levels of estrogen.

Estrogen may influence muscle fatigue or force generation by its potential to act as an antioxidant [1, 15] and by its ability to increase fat utilization and spare muscle glycogen in the intact exercising animal [6]. However, the lack of effect of estrogen administration on soleus muscle fatiguability in either gender suggest that these factors did not have significant influence on muscle function in this model and with the level and duration of estrogen administration employed. Since this protocol involved above normal levels of circulating estrogen, this could have had counterproductive effects on muscle function and may have negated any positive potential for estrogen to influence muscle function. Nevertheless, previous studies using supra-physiological estrogen dosages have reported improved muscle membrane stability and increased muscle glycogen sparing during exercise in male and female animals

[1, 6, 15]. It should be noted that the results of this study may not be generalized to skeletal muscles other than the soleus. It is possible that differences with muscle phenotype, activity level or function may interact differently with estrogen and therefore respond differently. These possibilities warrant further investigation. It is also possible that the rapid soleus fatigue induced by the stimulation protocol may have masked differences in fatigue rate. Future studies need to employ alternative fatigue protocols to determine their potential to affect estrogenic effect on *in vivo* muscle function.

Nevertheless, the results of this study tend to support the findings of Greeves *et al.* [5] who reported no effects of supraphysiological estrogen levels on maximal force generation and voluntary fatigue rate of the first dorsal interosseus muscle in young human females. Warren *et al.* [17] have also found similar peak torque values for the extensor digitorum longus (EDL) muscles following 150 eccentric contractions in ovariectomized mice with or without estrogen replacement. We have also not seen differences in fatigue rates of EDL muscles from estrogen injected or control animals using an in situ rat muscle preparation (unpublished observations).

The changes in $+dF/dt_{max}$ observed in this study mirror fatigue induced changes in Po. Changes in $+dF/dt_{max}$ are believed to be limited by the rate at which actin-myosin cross bridges enter force producing (strong binding) states from non-force producing (weak binding) states [8]. Hence, fatigue induced reduction in $+dF/dt_{max}$ likely reflects a lower fraction of cycling cross bridges in the force-generating state [8, 16]. Although factors such as myosin phosphorylation can positively affect this rate of transition in some muscles [16], it appears from results of this study that estrogen administration and/or gender does not have an effect on $+dF/dt_{max}$ in soleus muscle.

The lack of positive effect of estrogen on pre-fatigue Po or the rate of fatigue and recovery in male or female mouse soleus seen in the present study, were different from some previous reports. In contrast to our findings and that of Greeves *et al.* [5], Sarwar *et al.* [11] reported a slower rate of fatigue and greater strength in

quadriceps and hand grip contractions in young human females during menstrual phases coinciding with higher circulating estrogen levels. In addition, Skelton *et al.* [13] found increased voluntary adductor pollicis muscle strength in post-menopausal females taking estrogen replacement therapy. Other studies examining larger populations of pre-and post-menopausal females have also been contradictory as to the effectiveness of estrogen or estrogen replacement on voluntary muscle strength [2, 9]. Hence no clear answer as to the potential for estrogen to affect muscle force and fatiguability has yet emerged.

Some of this variability may be explainable by inter-study differences in estrogen dosage, length and/or timing of dosage, the muscles utilized and species differences. It is possible that the cyclical nature of changes in blood estrogen level as manifested during normal menstrual cycling may be an important factor in the potential of estrogen to affect muscle function. For example, Sarwar *et al.* [11].reported no change in muscle force or fatigue rates over the course of one menstrual cycle in females who were on oral contraceptives. Alternatively, Greeves *et al.* [5] have speculated on the possibility that progesterone or progesterone/estrogen interactions may be more important than changes in estrogen alone in affecting human muscle strength and fatiguability. The influence of these and other factors which may be associated with estrogenic effect on muscle contractile characteristics warrant further investigation.

In conclusion, this study did not find an effect of two weeks of estrogen administration on soleus muscle Po or $+dF/dt_{max}$ in male or female mice using *in vitro* muscle preparation. This suggests that if estrogen does affect soleus muscle function, this may not occur through direct influence on the muscle itself.

ACKNOWLEDGMENTS

This study was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

RELATIONSHIPS BETWEEN BODY BIOELECTRIC RESISTANCE AND SOMATOTYPE IN PRE-ADOLESCENCE CHILDREN

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ABSTRACT

The aim of this study was to investigate possible relationships between body resistance using multifrequency BIA and somatotype in pre-adolescence children. The subjects were 104 boys and 105 girls, 9–11 years of age. All children were on Tanner stage 1. Somatotype was estimated according to the protocol of Carter and Heath [3]. Extreme groups of body shape were separated on the bases of Carter and Heath [3] somatotype component dominancy: dominant ectomorphy (9 boys, 13 girls), dominant endomorphy (10 boys, 12 girls) and dominant mesomorphy (12 boys, 9 girls). Body resistance was measured using a multi-frequency impedance device MULTISCAN 5000 (UK). Body resistance was measured on the right side of the body followed by the measurement on the left side of the body. Resistance was also measured between hands and legs and diagonally between right hand and left leg and left hand and right leg of the body. Data at all frequencies (5–500 KHz) were analyzed, but only a part of the results is presented — 5 KHz as a measure of ECW, 50 KHz as a measure of TBW and 200 KHz as a measure of ICW. In all cases, mean resistance was significantly higher in girls in comparison with boys ($p < 0.001$). The influence of ectomorphy on the body resistance was significant only in total groups of boys ($r = 0.33 - 0.48$) and girls ($r = 0.21 - 0.43$). The relationships were mostly significant in girls in extreme endomorphy group. Mesomorphic component influenced negatively body resistance in boys ($r = -0.49 - 0.65$) and girls ($r = -0.30 - 0.45$). Regression analysis indicated that usually only mesomorphic component of somatotype was significant predictor of body resistance in boys

(34.0–38.9% of the total variance). Mesomorphy and ectomorphy components were usually added to the prediction models in girls (4.5–19.3% of the total variance). It was concluded that the somatotype highly influenced body resistance in preadolescence children.

Key words: somatotype, bioelectric resistance, children

INTRODUCTION

Bioelectrical impedance analysis is an inexpensive, simple and easy way to determine total body water (TBW) and fat-free mass (FFM) in children [9, 12, 22]. TBW and FFM are significantly related to stature squared devided by resistance (S^2/R) [21, 25]. High correlation coefficient ($r = 0.97$) has been reported between TBW and S^2/R in children and adolescents [9]. Danford *et al.* [8] indicated that S^2/R was found to be the single most significant predictor of TBW, accounting for 97% of the total variability in 5–9 year old healthy children. Much lower results have been obtained by Delozier *et al.* [10]. Stature and weight alone accounted for 0.70 of the variance in TBW. The addition of other anthropometric measures did not significantly increase the R^2 in 4 to 8 year old children [10].

Probably, stature is not the true conductor length when using the four-electrode wrist-to-ankle method of bioelectric impedance analysis (BIA). The true length of the conductor could be better represented by the acromial stature and the arm length [16]. On the other side, the FFM contains lesser concentrations of total minerals [14, 24], total body potassium [14, 26] and greater concentrations of TBW [14, 17, 18] in children. Probably, most of these factors will decrease the concentration of salt ions in the FFM, volume resistivity in ohm-cm is likely to be greater per unit of FFM in children.

New impedance instruments are able to measure body impedance at more than one frequency (50 KHz), ranging from low (about 1 KHz) to very high (> 1 MHz) [11]. At low frequency body impedance is a measure of extracellular water (ECW) and at high frequency is a measure of TBW.

Different segments of the body contribute to the resistance of the whole body to an extent that is out of prepartion to their contribution to body weight [4, 15]. For example, the thinner segment of the body provides greatest resistance especially when they are also tall [15]. Thus, the inclusion of other anthropometric dimensions in addition to stature into the regression equations will enhance the accuracy of the BIA method [1, 6].

Numerous attempts have been made to describe the form of the body based on somatotype classification methods. The Heath-Carter method [19] is the most commonly used method. This method is of particular interest because of the introduction of specific body shape concepts into the definition of three components of the physique. Endomorphy refers to relative fatness, mesomorphy relates to the robustness development and ectomorphy measures relative linearity of the body [19]. How three somatotype components and especially the extreme groups of body shape influence the body resistance in children is unknown.

The aim of this study was to investigate possible relationships between body resistance using multifrequency BIA and somatotype in pre-adolescence children.

MATERIAL AND METHODS

The subjects of this investigation were 104 boys and 105 girls, 9–11 years of age. The children were from several schools in Tartu, Estonia (about 100.000 inhabitants) and all the children were in estonian origin. Most of the children belong to the middle socio-economic class.

The children participated in 2–3 compulsory physical education lessons per week at school, which were conducted by a teacher of physical education. All children, parents and teachers were throughly informed about the purposes and contents of the study and written informed consent was obtained from the parents or the adult probands before participation. The study was approved by the Medical Ethics Committee of University of Tartu (Estonia).

All measurements were performed in the morning at school after emtying the bladder. All children had a light traditional breakfast. The children did not exercise before the testing. All children were on Tanner stage 1 [28]. The children were classified prepubertal as pubic hair and genitalia (boys), and breast (girls) ratings were both scored as stage 1.

Stature was measured using a Martin metal anthropometer in cm (± 0.1 cm) and body mass with medical scales in kg (± 0.05 kg). BMI (kg/m^2) was also calculated. In total, 4 skinfolds (triceps, subscapular, supraspinale, calf), 2 girths (biceps, calf) and 2 widths (humerus, femur) were measured. Anthropometric measurements were taken by a trained anthropometrist who had previously shown test-retest reliability of $r > 0.90$. The CENTURION KIT instrumentation was used (Rosscraft, Surrey, BC, Canada). Skinfold thicknesses were measured on the right side of the body using Holtain (Crymmych, UK) skinfold calipers. Two measures were taken, and when the difference between the two readings was more than 2 mm, a third measure was taken. The average of the two measures within 2 mm was considered as a true value.

Somatotype was estimated according to the protocol of Carter and Heath [3]:

a) Endomorphy = $-0.7182 + 0.1451(X) - 0.00068(X^2) + 0.0000014(X^3)$, where X is the sum of the triceps, subscapular and supraspinale skinfold adjusted for stature;
b) Mesomorphy = (0.858 biepicondylar + 0.601 bicondylar + 0.188 corrected arm circumference + 0.161 corrected calf circumference) – (stature × 0.131) + 4.50,
where corrected arm and calf circumferences are the respective limb circumferences minus the triceps and medial calf skinfolds, respectively;
c) Ectomorphy = HWR × 0.732 – 28.58,
where $HWR = \text{stature}/\sqrt[3]{\text{body weight}}$.
When HWR < 40.75 but > 38.25, ectomorphy = HWR × 0.463 – 17.63.
When HWR < 38.25, a rating of 0.1 is assigned.

When the calculation for any component is zero or negative, a value of 0.1 is assigned, the use by definition a rating can not be zero or negative [3].

Extreme groups for body shape were separated on the basis of Carter and Heath [3] somatotype component dominancy:
group 1: dominant ectomorph (9 boys, 13 girls, mean somatotype 5.49 – 1.59 – 2.95 and 5.63 – 1.40 – 2.73, respectively);
group 2: dominant endomorph (10 boys, 12 girls, mean somatotype 2.36 – 3.50 – 4.60 and 2.21 – 4.51 – 4.20, respectively);
group 3: dominant mesomorph (12 boys, 9 girls, mean somatotype 2.30 – 2.34 – 5.54 and 2.74 – 2.70 – 4.92, respectively).

Body resistance was measured using a multiple-frequency impedance device (MULTISCAN 5000, BODYSTAT Ltd, UK). Children were placed on a supine position with the limbs slightly abducted. Skin current electrodes were placed on the dorsal surface of the hand and foot at the metacarpals and metatarsals. Skin was cleaned with 70% alcohol and a small drop of EKG cream was used to improve current conduction between the electrode and skin. The distance between the source and the receiving electrodes was all times higher than 5 cm [4].

The MULTISCAN 5000 operates at a nominal current of 200 μA at frequencies from 5 to 500 KHz. In operation, the MULTISCAN 5000 was turned on and calibrated and resistance was measured automatically at the specified frequencies in a random order by the machine. The resistance data were stored on the hard disk of the computer. Body resistance of electrical current was measured on the right side of the body followed by the measurement on the left side of the body. Resistance was also measured between hands and legs, and diagonally between right hand and left leg, and left hand and right leg of the body. Data at all frequencies (5–500 kHz) were analysed, but only part of the results is presented — 5 KHz as a measure of ECW, 50 KHz as a measure of TBW and 200 KHz as a measure of ICW. Reproducibility and reliability of the BIA apparatuses have been reported to be lower at higher frequencies [5].

Descriptive statistics (mean ± standard deviation [SD]) for each of the dependent variables were determined. Differences between

boys and girls were estimated with independent t-tests with an error of estimate set to 0.05. Spearman correlation coefficients were used to determine the relationships between dependent variables. The effect of different somatotypes (independent variables) to the body resistance was analyzed by stepwise multiple regression analysis. Prediction errors for the equations were evaluated using the standard error of estimate (SEE). Significance was set at $p \leq 0.05$.

RESULTS

Physical characteristics of the children are presented in Table 1. Boys were older and their body weight and BMI were significantly ($p < 0.05$) higher than in girls. Girls were more endomorphy ($p < 0.05$) and boys were more mesomorphy ($p < 0.001$).

Table 1. Physical characteristics of the subjects ($\bar{X} \pm SD$)

	Boys (n = 104)	Girls (n = 105)	p
Age (yrs)	10.09 ± 0.84	9.79 ± 0.72	< 0.05
Stature (cm)	143.39 ± 7.27	141.49 ± 7.34	NS
Body mass (kg)	35.27 ± 5.71	33.29 ± 6.43	< 0.05
BMI (kg/m^2)	17.07 ± 1.78	16.50 ± 2.15	< 0.05
Ectomorphy	3.54 ± 1.10	3.76 ± 1.29	NS
Endomorphy	2.17 ± 0.92	2.55 ± 1.24	< 0.05
Mesomorphy	4.23 ± 0.91	3.75 ± 0.95	< 0.001

NS — not significant.

Mean anthropometrical parameters are presented in Table 2. Triceps and subscapular skinfolds were significantly ($p < 0.05$) thicker, biceps girth lower ($p < 0.05$) and both widths (humerus, femur) lower ($p < 0.01$) in girls.

Table 2. Anthropometrical parameters of the children ($\bar{X} \pm SD$)

	Boys (n = 104)	Girls (n = 105)	p
Skinfolds (mm)			
Triceps	9.97 ± 3.01	11.17 ± 3.91	< 0.05
Subscapular	7.33 ± 3.50	8.42 ± 5.06	< 0.05
Supraspinale	5.13 ± 2.56	6.20 ± 3.84	NS
Calf	12.32 ± 4.49	13.32 ± 5.18	NS
Girth (cm)			
Biceps	21.70 ± 2.01	20.98 ± 2.36	< 0.05
Calf	28.44 ± 2.37	28.25 ± 2.48	NS
Width (cm)			
Humerus	6.10 ± 0.38	5.82 ± 0.35	< 0.01
Femur	8.82 ± 0.46	8.36 ± 0.47	< 0.01

NS — not significant.

Mean body resistances measured in different frequencies and between different body sites are presented in Table 3. In all cases, mean resistance was significantly higher in girls in comparison with boys ($p < 0.001$). The mean difference between right and left side measurements at 50 KHz was 16.6 Ω (2.8%) and 17.2 Ω (2.7%) in boys and girls, respectively ($p < 0.001$). The body resistance measured diagonally (right hand — left leg or left hand — right leg) was similar and comparable with right and left side measurements ($p > 0.05$). However, the resistance measured between hands was significantly ($p < 0.001$) higher and resistance measured between legs significantly lower ($p < 0.01 - 0.001$) in comparison with the measurements of the other sites. Mean impedance index (S^2/R) on the right side of the body at 50 KHz was 36.14 ± 5.52 and 32.98 ± 5.14 in boys and girls, respectively ($p < 0.001$).

Table 3. Resistances and total body water (TBW), intracellular water (ICW) and extracellular water (ECW) measured at different sites of the body in boys and girls ($\bar{X} \pm SD$)

	Boys (n = 104)	Girls (n = 105)	p
Right side			
5 KHz (Ω)	622.4 ± 65.0	671.1 ± 68.9	< 0.001
50 KHz (Ω)	578.8 ± 58.3	626.8 ± 56.6	< 0.001
200 KHz (Ω)	522.8 ± 53.6	564.2 ± 50.6	< 0.001
TBW (l)	24.3 ± 2.6	20.1 ± 2.9	< 0.001
ICW (l)	12.3 ± 1.4	8.9 ± 1.2	< 0.001
ECW (l)	12.0 ± 1.3	11.3 ± 1.2	< 0.001
Left side			
5 KHz (Ω)	637.5 ± 66.0	692.9 ± 69.4	< 0.001
50 KHz (Ω)	595.4 ± 61.3	644.0 ± 60.6	< 0.001
200 KHz (Ω)	540.8 ± 58.5	587.3 ± 54.0	< 0.001
TBW (l)	23.8 ± 2.5	20.0 ± 2.3	< 0.001
ICW (l)	12.0 ± 1.5	8.8 ± 1.3	< 0.001
ECW (l)	11.9 ± 1.2	11.1 ± 1.1	< 0.001
Hand-hand			
5 KHz (Ω)	687.8 ± 74.4	759.9 ± 83.6	< 0.001
50 KHz (Ω)	650.3 ± 71.0	713.5 ± 72.5	< 0.001
200 KHz (Ω)	592.6 ± 65.2	653 3 ± 64.6	< 0.001
TBW (l)	23.1 ± 2.6	19.1 ± 2.2	< 0.001
ICW (l)	11.5 ± 1.7	8.5 ± 1.1	< 0.001
ECW (l)	11.6 ± 1.3	10.7 ± 1.3	< 0.001
Leg-leg			
5 KHz (Ω)	525.9 ± 53.5	581.3 ± 61.9	< 0.001
50 KHz (Ω)	485.1 ± 48.9	532.5 ± 60.0	< 0.001
200 KHz (Ω)	439.1 ± 47.3	480.5 ± 58.2	< 0.001
TBW (l)	25.9 ± 3.4	22.0 ± 2.7	< 0.001
ICW (l)	12.9 ± 2.1	9.8 ± 1.4	< 0.001
ECW (l)	13.0 ± 1.5	12.2 ± 1.4	< 0.001
Right hand-left leg			
5 KHz (Ω)	635.8 ± 67.3	711.1 ± 72.8	< 0.001
50 KHz (Ω)	592.7 ± 60.4	657.5 ± 65.0	< 0.001
200 KHz (Ω)	539.2 ± 55.8	595.9 ± 59.9	< 0.001
TBW (l)	23.8 ± 2.7	19.9 ± 2.4	< 0.001

	Boys (n = 104)	Girls (n = 105)	p
ICW (l)	11.9 ± 1.8	8.8 ± 1.3	< 0.001
ECW (l)	11.9 ± 1.2	11.1 ± 1.5	< 0.001
Left hand-right leg			
5 KHz (Ω)	632.4 ± 68.1	702.8 ± 69.5	< 0.001
50 KHz (Ω)	592.4 ± 61.7	650.8 ± 62.6	< 0.001
200 KHz (Ω)	539.2 ± 57.1	593.3 ± 51.6	< 0.001
TBW (l)	24.0 ± 2.7	19.9 ± 2.3	< 0.001
ICW (l)	12.0 ± 1.7	8.8 ± 1.2	< 0.001
ECW (l)	12.0 ± 1.3	11.0 ± 1.2	< 0.001

NS — not significant.

The relationships between age, stature, weight, BMI and body resistance are presented in Table 4. Stature only partly influenced body resistance in girls. More important are the body weight and BMI.

Table 4. The relationship of age, stature, weight and BMI to the body resistance (girls in brackets)

	Age	Stature	Weight	BMI
Right side				
5 KHz (Ω)	NS (–0.29)	NS (–0.20)	–0.44 (–0.43)	–0.47 (–0.46)
50 KHz (Ω)	NS (–0.35)	NS (–0.20)	–0.43 (–0.43)	–0.50 (–0.46)
200 KHz (Ω)	NS (–0.36)	NS (NS)	–0.41 (–0.41)	–0.51 (–0.46)
Left side				
5 KHz (Ω)	–0.20 (–0.36)	NS (NS)	–0.41 (–0.35)	–0.43 (–0.37)
50 KHz (Ω)	NS (–0.39)	NS (–0.24)	–0.42 (–0.46)	–0.47 (–0.47)
200 KHz (Ω)	NS (–0.38)	NS (–0.22)	–0.37 (–0.45)	–0.44 (–0.48)
Hand-hand				
5 KHz (Ω)	NS (–0.34)	NS (NS)	–0.37 (–0.35)	–0.44 (–0.39)
50 KHz (Ω)	NS (–0.32)	NS (NS)	–0.36 (–0.38)	–0.46 (–0.46)
200 KHz (Ω)	NS (–0.30)	NS (NS)	–0.35 (–0.36)	–0.47 (–0.42)
Leg-leg				
5 KHz (Ω)	–0.23 (NS)	NS (–0.28)	–0.39 (–0.36)	–0.43 (–0.30)
50 KHz (Ω)	–0.20 (NS)	NS (–0.28)	–0.39 (–0.36)	–0.43 (–0.29)
200 KHz (Ω)	NS (NS)	NS (–0.26)	–0.34 (–0.33)	–0.41 (–0.26)
Right hand-left leg				
5 KHz (Ω)	NS (–0.21)	NS (NS)	–0.35 (–0.32)	–0.44 (–0.33)
50 KHz (Ω)	NS (–0.21)	NS (–0.21)	–0.42 (–0.41)	–0.52 (–0.42)
200 KHz (Ω)	NS (–0.20)	NS (–0.20)	–0.39 (–0.42)	–0.50 (–0.44)

	Age	Stature	Weight	BMI
Left hand-right leg				
5 KHz (Ω)	–0.23 (–0.32)	NS (–0.22)	–0.44 (–0.41)	–0.49 (–0.43)
50 KHz (Ω)	–0.24 (–0.31)	NS (–0.22)	–0.44 (–0.44)	–0.50 (–0.47)
200 KHz (Ω)	–0.21 (–0.27)	NS (NS)	–0.41 (–0.42)	–0.49 (–0.46)

NS — not significant.

The Spearman correlations between body resistance measured at different sites of the body and somatotype components are presented in Tables 5–7. The influence of ectomorphy on the body resistance was significant only in the total group of boys and girls (Table 5). The relationships were not statistically significant ($p > 0.05$) in the extreme subgroups of ecto-, endo- and mesomorphy. The influence of endomorphy to the body resistance was not significant in boys and partly significant at a low level in girls (Table 6). The correlations were significant between endomorphy and resistance measured between hands ($r = 0.64 - 0.66$) in extreme ectomorphy group. The relationships were mostly significant in girls in extreme endomorphy group. The correlations were significant in most cases in boys and girls in extreme mesomorphy group (Table 6).

Table 5. The relationship of ectomorphy in total and extreme ectomorphy, endomorphy and mesomorphy groups to the body resistance (girls in brackets)

	Total (n = 104 and n = 105)	Extreme ectomorphy (n = 9 and n = 13)	Extreme endomorphy (n = 10 and n = 12)	Extreme mesomorphy (n = 12 and n = 9)
Right side				
5 KHz (Ω)	0.38 (0.40)	NS (NS)	NS (NS)	NS (NS)
50 KHz (Ω)	0.45 (0.41)	NS (NS)	NS (NS)	NS (NS)
200 KHz (Ω)	0.46 (0.43)	NS (NS)	NS (NS)	NS (NS)
Left side				
5 KHz (Ω)	0.35 (0.32)	NS (NS)	NS (NS)	NS (NS)
50 KHz (Ω)	0.41 (0.39)	NS (NS)	NS (NS)	NS (NS)
200 KHz (Ω)	0.40 (0.40)	NS (NS)	NS (NS)	NS (NS)

	Total (n = 104 and n = 105)	Extreme ectomorphy (n = 9 and n = 13)	Extreme endomorphy (n = 10 and n = 12)	Extreme mesomorphy (n = 12 and n = 9)
Hand-hand				
5 KHz (Ω)	0.40 (0.35)	NS (NS)	NS (NS)	NS (NS)
50 KHz (Ω)	0.43 (0.39)	NS (NS)	NS (NS)	NS (NS)
200 KHz (Ω)	0.45 (0.35)	NS (NS)	NS (NS)	NS (NS)
Leg-leg				
5 KHz (Ω)	0.33 (0.23)	NS (NS)	NS (NS)	NS (NS)
50 KHz (Ω)	0.38 (0.21)	NS (NS)	NS (NS)	NS (NS)
200 KHz (Ω)	0.39 (NS)	NS (NS)	NS (NS)	NS (NS)
Right hand-left leg				
5 KHz (Ω)	0.41 (0.29)	NS (NS)	NS (NS)	NS (NS)
50 KHz (Ω)	0.48 (0.36)	NS (NS)	NS (NS)	NS (NS)
200 KHz (Ω)	0.48 (0.38)	NS (NS)	NS (NS)	NS (NS)
Left hand-right leg				
5 KHz (Ω)	0.42 (0.37)	NS (NS)	NS (NS)	NS (NS)
50 KHz (Ω)	0.43 (0.42)	NS (NS)	NS (NS)	NS (NS)
200 KHz (Ω)	0.45 (0.42)	NS (NS)	NS (NS)	NS (NS)

NS — not significant.

Table 6. The relationship of endomorphy in total and extreme ectomorphy, endomorphy and mesomorphy groups to the body resistance (girls in brackets)

	Total (n = 104 and n = 105)	Extreme ectomorphy (n = 9 and n =13)	Extreme endomorphy (n = 10 and n = 12)	Extreme mesomorphy (n = 12 and n = 9)
Right side				
5 KHz (Ω)	NS (–0.29)	NS (NS)	NS (0.71)	NS (–0.84)
50 KHz (Ω)	NS (–0.27)	NS (NS)	NS (0.77)	NS (–0.79)
200 KHz (Ω)	NS (–0.26)	NS (NS)	NS (0.77)	NS (–0.86)
Left side				
5 KHz (Ω)	NS (–0.23)	NS (NS)	NS (NS)	–0.63 (–0.93)
50 KHz (Ω)	NS (–0.28)	NS (NS)	NS (NS)	–0.67 (–0.94)
200 KHz (Ω)	NS (–0.27)	NS (NS)	NS (NS)	–0.64 (–0.93)

	Total (n = 104 and n = 105)	Extreme ectomorphy (n = 9 and n =13)	Extreme endomorphy (n = 10 and n = 12)	Extreme mesomorphy (n = 12 and n = 9)
Hand-hand				
5 KHz (Ω)	NS (–0.21)	NS (0.66)	NS (0.72)	–0.72 (NS)
50 KHz (Ω)	NS (–0.25)	NS (0.64)	NS (0.72)	–0.70 (NS)
200 KHz (Ω)	NS (–0.24)	NS (0.65)	NS (0.72)	–0.69 (NS)
Leg-leg				
5 KHz (Ω)	NS (–0.19)	NS (NS)	NS (0.66)	NS (–0.96)
50 KHz (Ω)	NS (–0.19)	NS (NS)	NS (0.66)	NS (–0.97)
200 KHz (Ω)	NS (NS)	NS (NS)	NS (0.68)	NS (–0.97)
Right hand-left leg				
5 KHz (Ω)	NS (NS)	NS (NS)	NS (NS)	–0.61 (–0.79)
50 KHz (Ω)	NS (–0.23)	NS (NS)	NS (0.69)	–0.61 (–0.87)
200 KHz (Ω)	NS (–0.24)	NS (NS)	NS (NS)	–0.58 (–0.89)
Left hand-right leg				
5 KHz (Ω)	NS (–0.27)	NS (NS)	NS (0.71)	–0.73 (–0.79)
50 KHz (Ω)	NS (–0.31)	NS (NS)	NS (0.71)	–0.71 (–0.79)
200 KHz (Ω)	NS (–0.30)	NS (NS)	NS (0.73)	–0.66 (–0.78)

NS — not significant.

Mesomorphic component usually negatively influenced body resistance in boys and girls (Table 7). The relationships were not significant in girls and only partly significant in boys in extreme ectomorphy group. There were not any significant relationships in the extreme endomorphy group in boys and girls. There were significant correlations only in boys in the extreme mesomorphy group.

Regression analysis indicated that usually only mesomorphic component of the somatotype was significant predictor in boys (Table 8). Endomorphy was added to the prediction models only when the resistance was measured between legs or between left hand — right leg. These somatotype components characterized 34.0–38.9% of the total variance ($R^2 \times 100$). Mesomorphy and ectomorphy components were usually added to the prediction models in girls (Table 9). These somatotype components characterized only 4.5–19.3% of the total variance. This was two times lower than in boys. SEE was relatively high in all presented regression equations.

Table 7. The relationship of mesomorphy in total and extreme ectomorphy, endomorphy and mesomorphy groups to the body resistance (girls in brackets)

	Total (n = 104 and n = 105)	Extreme ectomorphy (n = 9 and n = 13)	Extreme endomorphy (n = 10 and n = 12)	Extreme mesomorphy (n = 12 and n = 9)
Right side				
5 KHz (Ω)	–0.55 (–0.41)	NS (NS)	NS (NS)	–0.62 (NS)
50 KHz (Ω)	–0.62 (–0.40)	–0.75 (NS)	NS (NS)	–0.58 (NS)
200 KHz (Ω)	–0.65 (–0.45)	–0.79 (NS)	NS (NS)	–0.63 (NS)
Left side				
5 KHz (Ω)	–0.51 (–0.33)	NS (NS)	NS (NS)	NS (NS)
50 KHz (Ω)	–0.60 (–0.41)	NS (NS)	NS (NS)	–0.59 (NS)
200 KHz (Ω)	–0.62 (–0.42)	–0.68 (NS)	NS (NS)	–0.65 (NS)
Hand-hand				
5 KHz (Ω)	–0.55 (–0.38)	NS (NS)	NS (NS)	–0.74 (NS)
50 KHz (Ω)	–0.62 (–0.42)	NS (NS)	NS (NS)	–0.64 (NS)
200 KHz (Ω)	–0.63 (–0.42)	–0.75 (NS)	NS (NS)	–0.66 (NS)
Leg-leg				
5 KHz (Ω)	–0.49 (NS)	NS (NS)	NS (NS)	–0.62 (NS)
50 KHz (Ω)	–0.58 (NS)	–0.73 (NS)	NS (NS)	NS (NS)
200 KHz (Ω)	–0.59 (NS)	–0.76 (NS)	NS (NS)	–0.64 (NS)
Right hand-left leg				
5 KHz (Ω)	–0.49 (–0.31)	NS (NS)	NS (NS)	–0.71 (NS)
50 KHz (Ω)	–0.62 (–0.38)	–0.81 (NS)	NS (NS)	–0.69 (NS)
200 KHz (Ω)	–0.64 (–0.38)	–0.86 (NS)	NS (NS)	–0.71 (NS)
Left hand-right leg				
5 KHz (Ω)	–0.53 (–0.36)	NS (NS)	NS (NS)	–0.75 (NS)
50 KHz (Ω)	–0.58 (–0.41)	–0.75 (NS)	NS (NS)	–0.64 (NS)
200 KHz (Ω)	–0.62 (–0.40)	–0.77 (NS)	NS (NS)	–0.66 (NS)

NS — not significant.

Table 8. Regression analysis of body resistance at 50 KHz with somatotype components in boys (n = 104)

	Intercept	F	$R^2 \times 100$	p	SEE
Right side	748.4	65.0	38.9	< 0.0000	45.8
Mesomorphy	–40.1				
Left side	767.0	57.5	36.1	< 0.0000	49.2
Mesomorphy	–40.6				
Hand-hand	855.6	64.1	38.6	< 0.0000	55.9
Mesomorphy	–48.6				
Leg-leg	614.1	28.7	36.2	< 0.0000	39.4
Mesomorphy	–35.4				
Endomorphy	9.5				
Right hand-left leg	767.9	64.7	38.8	< 0.0000	47.4
Mesomorphy	–41.5				
Left hand-right leg	755.7	26.0	34.0	< 0.0000	50.6
Mesomorphy	–42.3				
Endomorphy	7.1				

Table 9. Regression analysis of body resistance at 50 KHz with somatotype components in girls (n = 105)

	Intercept	F	$R^2 \times 100$	p	SEE
Right side	634.9	12.2	19.3	< 0.0002	51.3
Mesomorphy	–13.3				
Ectomorphy	11.2				
Left side	670.9	11.7	18.8	< 0.0003	55.2
Mesomorphy	–16.9				
Ectomorphy	9.7				
Hand-hand	757.1	12.2	19.3	< 0.0002	65.7
Mesomorphy	–22.2				
Ectomorphy	10.6				
Leg-leg	495.2	4.8	4.5	< 0.0030	58.9
Ectomorphy	9.9				
Right hand-left leg	684.1	9.8	16.3	< 0.0001	60.0
Mesomorphy	–16.8				
Ectomorphy	9.7				
Left hand-right leg	652.5	7.5	12.9	< 0.0009	58.9
Mesomorphy	–11.2				
Ectomorphy	10.7				

DISCUSSION

The estimation of body composition by BIA is a useful technique which can be executed rapidly, requires little skill of the technician or child. However, since the technique relies upon linear regression to predict body composition from S^2/R it is important to take into account other anthropometrical parameters such as body height. The somatotype, especially mesomorphic component has highly influenced body resistance in pediatric population.

Mean resistance of our children was comparable with the results of other studies where 10–14 year old children were measured [22]. The difference between right and left side measurements was statistically significant ($p < 0.001$) as in other studies [22]. There were not any statistically significant differences between resistance values measured in a traditional way or diagonally (right hand-left leg or left hand-right leg). Thus, our results confirm that the measurement of body resistance on the traditional right side of the body is correct in children.

Relatively inexpensive BIA analyzers have been used in health purposes were body resistance is measured between right and left legs (Tanita) or between hands (Omron). The lower body and upper body resistances measured by these analyzers is larger than whole-body resistance (right arm-trunk-right leg) because of the relatively smaller volumes of these body segments in comparison with the trunk [20]. In our study, the resistance measured between hands at 50 KHz was significantly higher when measured between right hand and left leg (Table 3). However, the resistance measured between legs was lower than measured at traditional sites.

There is a substantial evidence to suggest that such anthropometrical parameters as stature, weight, upper arm and calf circumferences and some skinfold thicknesses may significantly influence the whole body resistance in adults [1, 23, 25, 27]. Baumgartner *et al.* [1] demonstrated that 70% of the variance in resistance could be accounted for by a small set of anthropometric variables. It is interesting to note that the measure of weight and BMI were good predictors of body resistance also in preadolescence children (Table 4). This is not surprising, however, the fact that

weight (and BMI) had stronger predictive value than stature is important. In order to standardize for conductor length, stature is frequently used measurement in the classical BIA prediction equations. The finding that age also explains body resistance variation especially in girls (Table 4) supports other work showing age-dependent body composition prediction [13].

The high correlation between body resistance and mesomorphic component is not surprising (Table 7) as this component characterizes the relative musculosceletal robustness of the body, and derived from biepicondylar femur and humerus width, arm and calf circumferences corrected for skinfolds. This is highly correlated with body resistance. The multiple stepwise regression analysis indicated that mesomorphic component explained 34.0–38.9% of the total variance.

The ectomorphic component in combination with mesomorphy characterized only 20% of the total variance in girls (Table 9). Thus, especially in girls, the relative linearity (ectomorph) and robustness (mesomorph) are the components which highly influence body resistance. However, there are opinions that the three components of somatotype are not independent from one another [2, 7]. Ectomorphy, however, is often loaded by the same factors as for other components and is, therefore, defined as a negative pole of endomorphy-mesomorphy.

Endomorphy, which characterizes the relative fatness of the body is negatively influenced by the body resistance only in the total group of girls (Table 6). This was somewhat surprising, because the fat component of the body is nonconductive. There was not any overweight children in our groups. Probably, the children who have a relatively high amount of body fat have a relatively high amount of lean body weight at the same time also. Lean body weight is a good electric conductor. Thus, the significant positive correlation is understandable in the extreme endomorphy group.

It was concluded that somatotype highly influenced body resistance in pre-adolescence children.

ACKNOWLEDGMENTS

We express thanks to prof. ALBRECHT CLAESSENS and prof. HAN KEMPER for their comments and suggestions.

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

AEROBIC AND ANAEROBIC ENERGY RELEASE DURING 10 AND 30 S BICYCLE SPRINTS

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ABSTRACT

To study the energy release during very high intensity exercise, nine moderately trained young men first cycled at 13.1 ± 0.3 W kg^{-1} body mass for 12.5 ± 1.1 s (mean ± SEM) to exhaustion (called 10 s sprint). After a 1 h rest they cycled at 9.5 ± 0.3 W kg^{-1} for 31 ± 3 s to exhaustion (30 s exercise). Muscle biopsies were taken before and immediately after both exercises and analyzed for lactate and phosphocreatine (PCr). In addition the O_2 uptake was measured, and the rate of ATP-turnover was calculated from the measured O_2 uptake, the calculated use of stored O_2, and the measured changes in muscle metabolites. The muscle lactate concentration rose by 11.2 ± 1.4 mmol·kg^{-1} wet muscle mass (mean ± SEM; 10 s sprint), and by 19.6 ± 1.1 mmol·kg^{-1} (30 s exercise). The PCr concentration fell by 7.1 ± 0.8 and 10.6 ± 0.8 mmol·kg^{-1} for the two exercises, while the ATP-concentration fell by 0.5 ± 0.2 mmol·kg^{-1}. The post-exercise PCr concentration of 7–9 mmol·kg^{-1} suggests that there was a considerable energy reserve at exhaustion. For the 10 s exercise aerobic processes, lactate production, and PCr + ATP breakdown provided 31, 47, and 22%, respectively, of the energy released during the sprint, while for the 30 s exercise the corresponding values were 38, 45, and 17%. There was no apparent delay from the onset of exercise to the onset of lactate production and aerobic processes. The ATP turnover rate was compared with values obtained at lower powers and seemed to rise linearly by the power. Thus, the exercise economy taken as the ratio between the work

done and the calculated ATP turnover did not differ significantly between exercise at very high and moderate intensities.

Key words: ATP; Energy release; Energy metabolism; Exercise; Exercise economy; Lactate; Muscle energetics; Muscle metabolism; Oxygen consumption; Oxygen deficit; Oxygen uptake; Phosphocreatine; Power output.

INTRODUCTION

Working muscles release energy by splitting ATP, probably in proportion to the exercise intensity. The ATP store in muscles is limited and does not change much during exercise [3, 5–7, 16, 25, 26, 33]. Therefore, resynthesis of ATP takes place almost as fast as ATP is broken down. ATP is resynthesized enzymatically by aerobic and anaerobic processes. The two quantitatively most important anaerobic processes are phosphocreatine breakdown and the glycolytic production of lactate. Lactate is produced with little delay at the onset of intense exercise [10, 14–16], and both lactate production and phosphocreatine breakdown are important processes. There is on the other hand not much information on the O_2 uptake and the importance of aerobic processes during short bursts of exercise.

At low to moderate exercise intensities the mechanical efficiency or exercise economy, defined as the ratio between the amount of work done and the amount of energy released, is calculated from the measured O_2 uptake. O_2 is consumed to resynthesize ATP, and another physiologic measure of the exercise economy is the ratio between the work done and the ATP turnover. This measure allows for a comparison of the economy between aerobic and anaerobic energy release and exercise at moderate and high intensities. We have proposed that the accumulated O_2 deficit measures the anaerobic energy release during high intensity exercise [22, 24, 25]. This method is based on a linear extrapolation procedure that assumes a constant economy, but the exercise economy is not known for exercise at very high intensities.

To examine the energy release and the economy during high exercise intensities, we let subjects cycle at constant power for ≈10 s to exhaustion. For a comparison with data from our former studies [24, 25], the subjects did an additional 30 s exhausting ride at a lower power. The anaerobic energy release was determined independently from muscle biopsies and from whole body measures of the energy release. The aerobic energy release was taken from the measured O_2 uptake and the assumed use of stored O_2. We hypothesized that both aerobic and anaerobic processes are important for 10 s sprints. Moreover, we hypothesized that the exercise economy may not differ much between moderate and high intensities.

SUBJECTS AND METHODS

Subjects

Nine men 28 ± 3 yr old (mean ± SD), 1.81 ± 0.05 m tall, weighing 78 ± 8 kg and with a maximal O_2 uptake of 41 ± 3 $\mu mol \cdot s^{-1} \cdot kg^{-1}$ (54 ± μ 5 $ml_{STPD} \cdot min^{-1} \cdot kg^{-1}$) gave their written consent to serve as subjects in the experiments. The experimental protocol was approved by the Regional Ethics Committee.

Procedures

Exercise was carried out on an electrically braked Krogh-type bicycle ergometer [17] at 2.0 Hz (120 rpm) pedaling frequency. For the 10 s sprints described below the frequency was set to 2.1 Hz to compensate for the delay at the onset of exercise due to the start from zero speed. The frequency was continuously shown to the subjects on an analog instrument. The ergometer was equipped with a work meter counting the number of revolutions of the flywheel (6 rev s-1 at 2 Hz) and thus recording the work done accurately since also the flywheel's runoff after each experiment was

included. The reported power is the ratio between the recorded work and the exercise duration recorded by a stop watch. Only negligible deviations between the preset and the actual power were found in all experiments.

The bicycle ergometer was equipped with flat pedals without straps around the foot. Thus, work was done on the ergometer only during the downward push.

Pretests

Each subject went through several pretests during the weeks before the experiments. First, the maximal O_2 uptake was determined by the leveling off criterion [30]. Second, a linear relationship between the power and the O_2 demand was established for each subject as follows: The O_2 uptake was measured from 8 to 10 min of exercise at constant intensity below the maximal O_2 uptake. The anaerobic contribution is negligible during these conditions, and the measured O_2 uptake thus equals the O_2 demand or the rate of ATP-turnover expressed in O_2 units [24]. This procedure was carried out more than ten times (13 ± 3, mean ± SD) at powers between 30 and 90% of the maximal O_2 uptake [22, 24]. The mean (±SD) regression parameters were: Y-intercept, 12 ± 2 μmol O_2 $s^{-1} \cdot kg^{-1}$ body mass (16 $ml_{STPD} \cdot min^{-1} \cdot kg^{-1}$); slope, 7.8 ± 0.4 μmol O_2 J^{-1} (175 $ml \cdot J^{-1}$); error of regression (scatter around the regression line), 0.58 ± 0.14 μmol O_2 $s^{-1} \cdot kg^{-1}$ (0.8 $ml \cdot min^{-1} \cdot kg^{-1}$); correlation coefficient, 0.996 ± 0.002. Third, the highest power that could be maintained for ≈10 s and ≈30 s was established by trial and error.

Experiments

On the day of the experiment each subject arrived at the laboratory in the morning after an overnight fast. Local anesthesia (Xylocain, 10 g L-1) was given, and two incisions in the skin and muscle fascia were made over the lateral portion of the quadriceps muscle of

each thigh. Thereafter the subject warmed up for 10 min at 50% of his maximal O_2 uptake before the preexercise muscle biopsies were taken. The subjects cycled for about 10 s at the preset power to exhaustion while expired air was collected in a Douglas bag to measure the O_2 uptake. Exhaustion is here defined as inability to keep the preset pedaling rate and power. While the subjects were sitting on the bicycle ergometer, muscle biopsies were taken from both legs and frozen in freon-22 cooled by liquid N2 (the delay from the end of the exercise to freezing was 11.1 ± 0.6 s; mean ± SEM). Blood samples taken from a prewarmed finger as soon as possible after exercise (41 ± 3 s), and 2, 5, 8, 11, 15, 20, and 30 min after exercise were analyzed for lactate.

In the second experiment carried out after a 1 h break, the subject exercised for around 30 s to exhaustion. The same procedures as for the 10 s experiment were repeated. The biopsy sites before and after the two exercises were randomized by a Latin square procedure. Biopsies were not taken from one subject. Data from two subjects each carrying out a third exercise to exhaustion where no biopsies were taken have also been included.

Analyses

O_2 uptake. The volume of expired air was measured in a wet spirometer, while the fractions of CO_2 and O_2 were measured on an automatic system (CO_2 on an analyzer from Simrad Optronics, Oslo, Norway; O_2 on an S 3A/I analyzer from Ametek, Pittsburgh, PA, USA).

Biochemical analyses. Blood and muscle lactate and muscle glycogen, glucose, and glucose-6-phosphate (G-6-P) concentrations were measured enzymatically [18]. Muscle phosphocreatine and ATP concentrations were measured in neutralized perchloric acid extracts of muscle biopsies by a luminometric method using firefly luciferase (EC 1.13.12.7; Bio-Orbit, Turku, Finland; Ref 19). For the biopsies from one subject phosphocreatine and ATP were also analyzed by enzymatic photofluorometry [18]. Muscle glycogen was measured both on the supernatant and on the precipitate after

neutralization of the perchloric acid with potassium bicarbonate [20]. All values are expressed per kilogram wet muscle mass or per liter of blood. Our former study showed no fluid uptake in working muscles during exercise lasting only 30 s (25). Therefore no correction was made for possible changes in muscle fluid content. All chemicals used were of analytical grade.

Calculations

The O_2 demand for the two experiments was estimated by linear extrapolations of the individual relationships between power and the steady state O_2 uptake. The standard errors of the prediction (SEP) were 2.5 ± 0.2 (10 s) and 1.6 ± 0.2 μmol O_2 $s^{-1} \cdot kg^{-1}$ body mass (30 s), which is 2% of the predicted value in both cases. The accumulated O_2 demand is the O_2 demand times the exercise duration. The accumulated O_2 uptake is the O_2 uptake integrated over the exercise period. The accumulated O_2 deficit during exercise is the difference between the accumulated O_2 demand and the accumulated O_2 uptake [22]. Around 0.25 mmol $\cdot kg^{-1}$ of the accumulated O_2 deficit is due to use of stored O_2 (mainly in venous blood) during exercise [22, 24], and in further calculations this value has been subtracted from the reported accumulated O_2 deficit to give better estimates of the true whole body anaerobic energy release. Dividing this corrected accumulated O_2 deficit by the exercise duration gives the mean rate of anaerobic energy release in O_2 units. The mean rate of aerobic energy release was likewise taken as the accumulated O_2 uptake plus 0.25 mmol O_2 kg^{-1}, divided by the exercise duration.

The respiratory exchange ratio was 0.9 or larger and varied little between the 10 min bouts of exercise. Therefore, no correction was made to account for the fact that carbohydrate oxidation provides more ATP than fat oxidation per mole of O_2 consumed.

The anaerobic ATP-production was calculated as

$$ATP_{Anae} = 1.5 \cdot \Delta[La] - \Delta[PCr] - \Delta[ATP]$$

The latter two changes were negative during the exercises. A possibly further degradation of ADP is disregarded. Our calculations

of the energy release also disregards accumulation of pyruvate and triose phosphates. However, the concentration of these muscle metabolites is low even after exercise [5, 7, 26], and the error introduced is therefore regarded of no importance. The calculation also neglects possible release of lactate to the blood during the exercises. That error is quite small even for bicycling lasting more than 2 min [20, 23], and for exercise lasting some seconds there may be little time for lactate release. The low blood lactate concentrations at the end of exercise support that conclusion.

It could be argued that lactate released from working muscles was taken up by inactive muscles. This effect may be negligible since Bangsbo *et al.* [4] found an uptake of around 3 $\mu mol \cdot s^{-1} \cdot kg^{-1}$ muscle. If the nonactive muscle mass in our study was 20% of the body mass and Bangsbo's data hold for our subjects, the calculated uptake would be 7 (10 s) and 19 μmol lactate kg^{-1} body mass (30 s bouts), which is only 0.3 and 0.4%, respectively, of all lactate produced during the exhausting exercises.

To compare energy release expressed per muscle mass and per body mass, the anaerobic energy release should in principle be taken from changes in the lactate and phosphocreatine concentrations integrated over the whole body mass. We used data on the muscle biopsies and assumed that these data represented a working muscle mass equal to 25% of the body mass. The value of 25% was not measured, but it is supported by data from a bicycle study of Sahlin *et al.* [29] where muscle biopsies were taken and the accumulated O_2 deficit at the onset of exercise was determined without any extrapolation. Moreover, biomechanical analyses by Ericson *et al.* [9] show that the knee extensors do around one third of the work during bicycling. In a parallel study we calculated the volume of the knee extensors, the gluteus maximum and adductor magnus muscles by measuring their cross-sections on serial cross-sections from the knee to the iliac crest taken by computerized tomography. The volume or mass of these three muscles was 8%, 4%, and 4%, respectively, of the body mass. Others have found that the muscle mass in one thigh of healthy young men is around 10% of the body mass [4]. Thus, our and others measurements [4]

and Ericson's [9] biomechanical analyses also suggest that the working muscle mass was around 25% of the body mass.

Amounts of O_2 are expressed in ATP-units by taking 1 mol of O_2 equal to 6.5 mol of ATP as for oxidation of carbohydrates. For a comparison with data presented in this study, the maximal O_2 uptake of 41 $\mu mol \cdot s^{-1} \cdot kg^{-1}$ corresponds to an ATP turnover rate of 0.27 $mmol \cdot kg^{-1}$ body mass or 1.07 $mmol \cdot kg^{-1}$ muscle mass using the conversions above.

We have made no corrections for the metabolism in nonactive tissues. The resting metabolism was 2–3% of the O_2 demand during exercise, and the error is therefore regarded as negligible in this context.

Statistics and data handling

The data are given as individual results or as mean ± SEM. Linear regressions were calculated by least square methods in Sigmaplot (Jandel Sci, Erkrath, Germany, individual relationships between power and O_2 demand) or as the geometric mean (the regressions line in Figure 1, Ref 28), and the error of regression (scatter around the regression line, $S_{Y|x}$) was used as a measure of the goodness of the fit.

For two subjects some of the data on the O_2 uptake were lost because of technical problems with the O_2 analyzer. These data and entities calculated from them (the O_2 demand and derived entities) are therefore not reported for these two subjects.

RESULTS

Work, power, and duration

During the so called 10 s bout the subjects cycled at 13 W kg^{-1} for 12 s to exhaustion (Table 1). During the so called 30 s bout the subjects cycled at 9.5 W kg^{-1} for 31 s to exhaustion. When comparing the data of the 10 s ride with those of the 30 s exercise, the

duration was 40% of the duration of the second sprint, the mean power was 38% larger, while the work done was 57% of the value of the 30 s exercise.

Table 1. Exercise duration, work, and whole body measures of energy release during exercise

Exercise bout	10 s	30 s
Exercise duration (s)	12.5 ± 1.1	31.2 ± 2.8
Work (J kg^{-1} body mass)	166 ± 16	293 ± 19
Power (W kg^{-1} body mass)	13.1 ± 0.3	9.5 ± 0.3
Accumulated O_2 demand (mmol·kg^{-1} body mass)	1.41 ± 0.17	2.67 ± 0.21
Accumulated O_2 uptake (mmol·kg^{-1} body mass)	0.16 ± 0.04	0.78 ± 0.10
Accumulated O_2 deficit (mmol·kg^{-1} body mass)	1.25 ± 0.15	1.89 ± 0.14
O_2 demand (μmol·s^{-1}·kg^{-1} body mass)	114 ± 4	86 ± 4
(mmol ATP s^{-1}·kg^{-1} body mass)	0.74 ± 0.02	0.56 ± 0.02
(relative to the maximal O_2 uptake)	2.77 ± 0.09	2.10 ± 0.10
O_2 uptake (μmol s^{-1}·kg^{-1} body mass)	12 ± 3	24 ± 2
O_2 deficit (μmol s^{-1}·kg^{-1} body mass)	102 ± 3	62 ± 4
Rate of aerobic energy release		
(μmol O_2 s^{-1}·kg^{-1} body mass)	33.8 ± 2.9	32.8 ± 1.5
(μmol ATP s^{-1}·kg^{-1} body mass)	219 ± 19	213 ± 10
Rate of anaerobic energy release		
(μmol O_2 s^{-1}·kg^{-1} body mass)	80 ± 5	53 ± 3
(μmol ATP s^{-1}·kg^{-1} body mass)	521 ± 32	346 ± 21

The data are mean ± SEM for n = 7 subjects (n = 9 for the exercise duration, power, and work). Tne aerobic rate of energy release has been calculated by adding 0.25 mmol·kg^{-1} to the accumulated O_2 uptake before dividing by the exercise duration. The anaerobic rate has been calculated by subtracting 0.25 mmol·kg^{-1} from the accumulated O_2 deficit before dividing by the exercise duration.

Whole body measures of the energy release

The accumulated O_2 uptake rose linearly by the exercise duration at a rate of 32 μmol·s^{-1}·kg^{-1} body mass after an 8 s delay (Figure 1); that rate of increase corresponds to 79% of the subjects' maximal O_2 uptake. As stated in the methods, around 0.25 mmol stored O_2 kg^{-1} body mass is used before O_2 an increase in the O_2 uptake is seen. Thus, since the Y-intercept is similar in magnitude

to this amount of O_2, these data suggest that O_2 is consumed in the muscles with almost no delay. The accumulated O_2 demand of the 10 s exercises was 47% less than for the 30 s bouts (Table 1). The accumulated O_2 deficit was the major component of the accumulated O_2 demand for both exercises, but there was a significant O_2 uptake even for the 10 s rides.

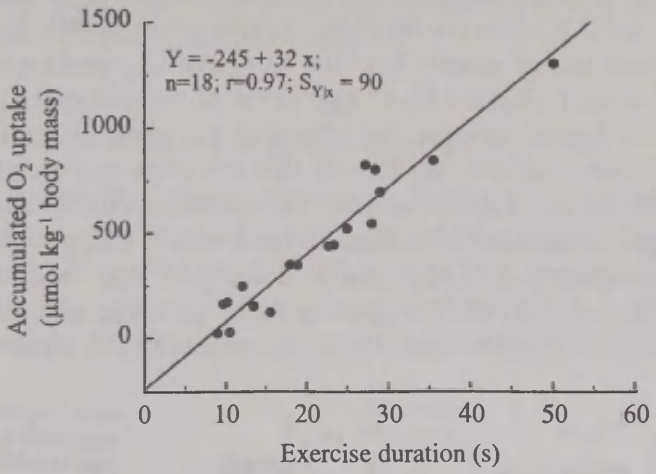

Figure 1. Accumulated O_2 uptake versus the exercise duration for 10 and 30 s bicycling to exhaustion. The Y-intercept of –0.245 mmol O_2 kg^{-1} body mass is similar in magnitude to the assumed use of stored O_2 at the onset of exercise. The regression line was calculated as the geometric mean [28].

For the 10 s exercises the accumulated O_2 deficit corrected for the assumed use of stored O_2 was 39% less than the corresponding value of the 30 s exercises. Adding the assumed use of stored O_2 to the accumulated O_2 uptake of the 10 s exercises gives a value of 0.4 mmol·kg^{-1} body mass (29% of the accumulated O_2 demand). It should be noted that around 60% of this value stems from the assumed use of stored O_2. For the 30 s exercise the corresponding estimated aerobic energy release was 1.0 mmol·kg^{-1} or 37% of the

accumulated O_2 demand. All these values are expressed per kg of body mass.

Rates of energy release

The O_2 demand of the 10 s exercises was 114 $\mu mol \cdot s^{-1} \cdot kg^{-1}$ body mass. This is 33% larger than the corresponding value of the 30 s exercise and 2.8 times the maximal O_2 uptake (Figure 2). Adding the assumed use of stored O_2 to the measured O_2 uptake gives a value of around 33 $\mu mol\ O_2\ s^{-1} \cdot kg^{-1}$ (83% of the maximal O_2 uptake) for both exercise durations (Table 1); the whole difference in the O_2 demand between the 10 and 30 s exercises thus seemed to be covered by anaerobic processes. The estimated rates of anaerobic energy release after correcting for the assumed use of stored O_2 were consequently 80 (10 s) and 53 $\mu mol\ O_2\ s^{-1} \cdot kg^{-1}$ body mass (30 s). The rate for the 10 s sprint is twice the subjects' maximal O_2 uptake, and it is 50% higher than the value of the 30 s bouts.

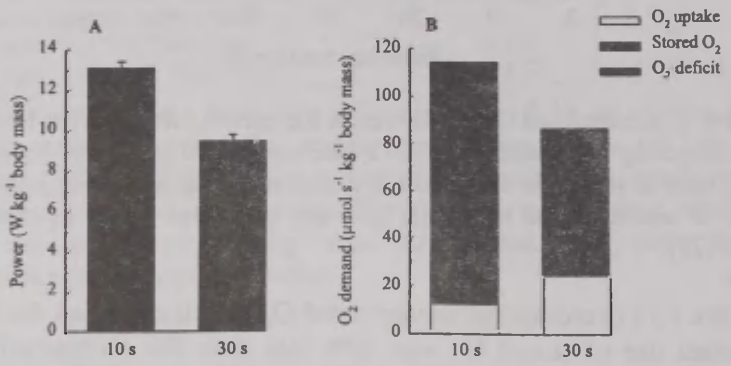

Figure 2. Power output (**A**) and the O_2 demand (**B**) for 10 and 30 s bicycling to exhaustion. In panel B the O_2 uptake is given by open bars (□), the use of stored O_2 is given by gray bars (▒), while the O_2 deficit corrected for use of stored O_2 is given by black bars (■). The data are mean (± SEM) for seven subjects.

Muscle and blood metabolites

The pre-exercise concentrations of muscle metabolites were 87 ± 6 mmol·kg^{-1} for glycogen, 0.7 ± 0.1 mmol·kg^{-1} for glucose, 0.15 ± 0.02 mmol·kg^{-1} for glucose-6-phosphate, 1.9 ± 0.1 mmol·kg^{-1} for lactate, 16.8 ± 0.5 mmol·kg^{-1} for phosphocreatine, and 3.9 ± 0.1 mmol·kg^{-1} for ATP. All values are expressed per kilogram wet muscle mass. The pre-exercise values did not differ significantly between the two bouts carried out.

Amounts of anaerobic energy release

During the 10 s exercise the muscle lactate concentration rose by 11 mmol·kg^{-1} wet muscle mass, and the phosphocreatine concentration fell by 7 mmol·kg^{-1}. During the 30 s exercise the lactate concentration rose by 20 mmol·kg^{-1}, and the phosphocreatine concentration fell by 11 mmol·kg^{-1} (Table 2, Figure 3). During both

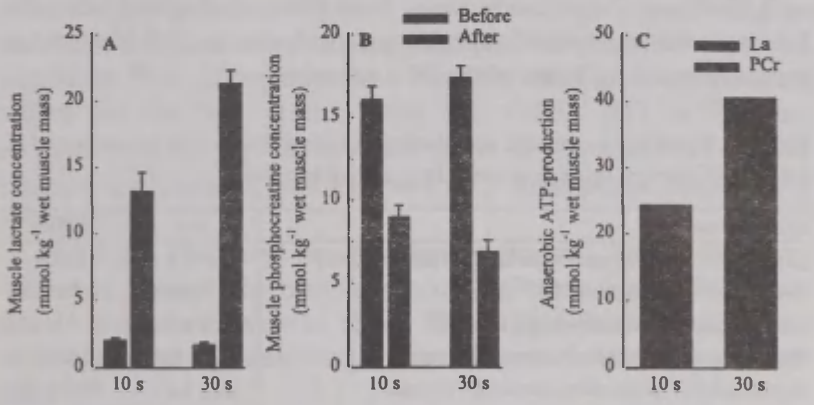

Figure 3. Muscle lactate (**A**) and phosphocreatine concentrations (**B**) before and after exercise, and the anaerobic ATP-production (**C**) for 10 and 30 s bicycling to exhaustion. The data are mean ± SEM for seven subjects.

rides the ATP concentration fell by 0.55 ± 0.14 mmol·kg^{-1}. The anaerobic ATP production of 24 mmol·kg^{-1} wet muscle mass for the 10 s sprint was 40% less than the value of the 30 s exercise. Lactate production accounted for 68 (10 s) and 72% (30 s; P = 0.06) of the anaerobic ATP-production.

Rates of energy release

The mean rate of lactate production of 0.88 mmol s^{-1}·kg^{-1} wet muscle mass during the 10 s sprint was 33% higher than the value of the 30 s exercise (Table 2). The mean rate of phosphocreatine breakdown was 68% higher during the 10 s than during the 30 s exercise. Consequently, the mean rate of anaerobic ATP-production was 39% higher during the 10 s sprints. Adding the aerobic rate of energy release taken from the measured O_2 uptake and the assumed use of stored O_2 gives a value of the total rate of ATP-turnover of 2.7 mmol·s^{-1}·kg^{-1} wet muscle mass for the 10 s sprint or 0.67 mmol·s^{-1}·kg^{-1} body mass. This value corresponds to a rate 2.5 times the maximal O_2 uptake, and the value is 21% higher than the corresponding value of the 30 s exercise.

Table 2. Changes in muscle metabolite concentrations and measures of the rate of energy release in muscle during exercise

Exercise bout	10 s	30 s
Glycogen breakdown (mmol glu·kg^{-1} wet muscle mass)	7 ± 5	22 ± 4
G-6-P accumulation (mmol·kg^{-1} muscle)	2.2 ± 0.3	2.7 ± 0.3
Lactate accumulation (mmol·kg^{-1} muscle)	11.5 ± 1.4	19.6 ± 1.1
Phosphocreatine breakdown (mmol·kg^{-1} muscle)	7.1 ± 0.8	10.6 ± 0.8
Anaerobic ATP-production (mmol·kg^{-1} muscle)	24.4 ± 2.3	40.6 ± 1.8
Relative contribution from lactate production	0.68 ± 0.03	0.72 ± 0.02
Mean glycogenolytic rate (mmol·glu·s^{-1}·kg^{-1} muscle)	0.60 ± 0.07	0.42 ± 0.04
Mean rate of lactate production (mmol·s^{-1}·kg^{-1} muscle)	0.88 ± 0.09	0.66 ± 0.06
Mean rate of PCr + ATP breakdown (mmol·s^{-1}·kg^{-1} muscle)	0.59 ± 0.12	0.34 ± 0.03
Mean anaerobic ATP turnover rate (mmol·s^{-1}·kg^{-1} muscle)	1.93 ± 0.17	1.39 ± 0.14
Mean rate of aerobic ATP turnover (mmol·s^{-1}·kg^{-1} muscle)	0.82 ± 0.07	0.83 ± 0.04
(relative to the total)	0.33 ± 0.02	0.38 ± 0.03

Exercise bout	10 s	30 s
Total ATP turnover rate ($mmol \cdot s^{-1} \cdot kg^{-1}$ muscle mass)	2.69 ± 0.21	2.22 ± 0.15
($mmol \cdot s^{-1} \cdot kg^{-1}$ body mass)	0.67 ± 0.05	0.56 ± 0.04
(relative to the maximal O_2 uptake)	2.5 ± 0.2	2.1 ± 0.2

The data are mean ± SEM, n = 8 (n = 7 for the calculated aerobic and total rates) and expressed per kg of wet muscle mass unless otherwise stated. glu, glucosyl units; G-6-P, glucose-6-phosphate; PCr, phosphocreatine. The anaerobic ATP-production and rate are calculated from measured changes in muscle lactate, PCr, and ATP concentrations. The glycogenolytic rate is calculated from measured changes in muscle glucose, G-6-P, and lactate concentrations. The aerobic rate is taken from the measured O_2 uptake plus the assumed use of stored O_2. The total rate is the sum of the aerobic and anaerobic rates.

To compare the different components of the energy release, all rates were expressed in ATP-units per kg of body mass. For the 10 s sprints the aerobic rate of ATP-production (including the assumed use of stored O_2), glycolysis, and breakdown of phosphocreatine and ATP provided 213 (31%), 330 (47%), and 154 µmol ATP $s^{-1} \cdot kg^{-1}$ body mass (22% of the total) respectively. Thus, even for the 10 s sprints aerobic processes seemed quantitatively more important than phosphocreatine breakdown. The corresponding values for the 30 s sprints were 213 (38%), 247 (45%), and 94 µmol ATP $s^{-1} \cdot kg^{-1}$ body mass (17% of the total) for aerobic processes, glycolysis, and PCr and ATP breakdown, respectively (Figure 4).

For both exercises the glycogenolytic rate as judged from measured changes in muscle glucose, glucose-6-phosphate, and lactate concentrations was about 30% higher than the glycolytic rate taken from the measured changes in muscle lactate concentration.

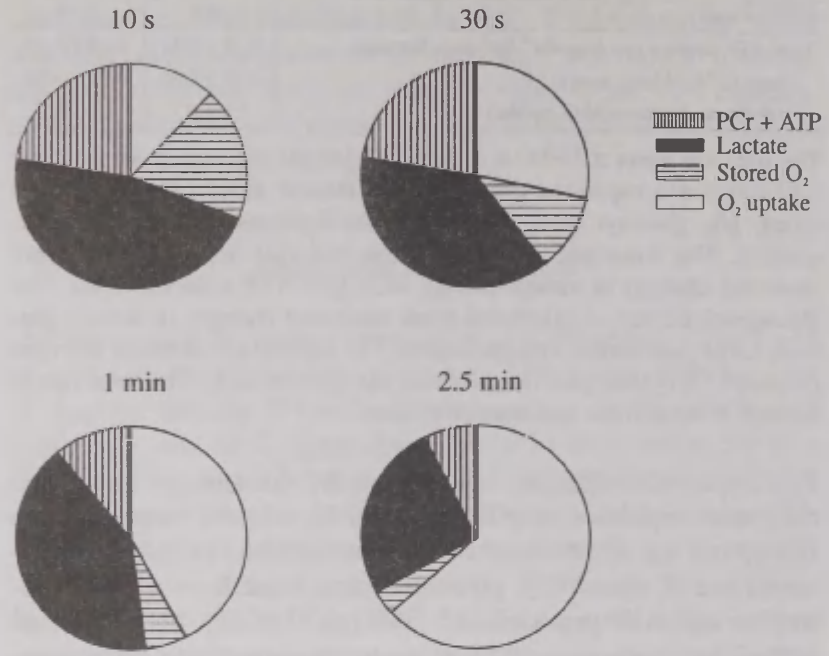

Figure 4. Relative contribution to the energy release for exhausting exercise lasting 10 and 30 s (present study), and 1 and 2–3 min [25]. The sectors represent (in the positive or counter clockwise direction starting at the 100 gon or 12 o'clock position) phosphocreatine (gray, hatched), lactate (black), stored O_2 (white, hatched), and O_2 uptake (white) The data are mean values from 7–9 subjects in each case.

Blood lactate concentration

The blood lactate concentration before exercise was 1.9 ± 0.4 mmol·L^{-1}, and it rose by 1.3 mmol·L^{-1} during the 10 s sprint and by 4.2 mmol·L^{-1} during the 30 s ride as judged from blood samples taken 41 ± 3 s after exercise. The peak postexercise blood lactate concentrations found 5 min after the exercise were 8.5 ± 0.6 (10 s) and 11.6 ± 0.5 mmol·L^{-1} (30 s).

Exercise economy

The accumulated O_2 deficit and the anaerobic ATP-production in muscle, two independent measures of the anaerobic energy release, were quantitatively similar provided that the muscle biopsy data were representative of a working muscle mass of 25% of the body mass (Figure 5A). While the calculated anaerobic rate of ATP-turnover is taken from measured changes in muscle metabolites, the accumulated O_2 deficit is calculated assuming a constant exercise economy. The data in figure 5a are thus compatible with the idea that the exercise economy does not change with the exercise intensity. If the economy of high-intensity exercise was less than of exercise at lower intensities, the values should have been above the line. The figure shows some deviations. The three largest deviation from our former study [25] are all from the same subject. This could mean that our assumptions that the biopsy data are representative of a working muscle mass equal to 25% of the body mass is incorrect for this subject.

To examine the economy further the total rate of energy release was calculated from the measured O_2 uptake, the assumed use of stored O_2, and the measured changes of muscle lactate, phosphocreatine, and ATP concentrations. The total rate of energy release, expressed in ATP-units kg^{-1} body mass as explained further in the method section, rose linearly by the power (Figure 5B). The calculated rates fell around the line found by extrapolating the subjects relationship at moderate intensities with little if any anaerobic energy release.

DISCUSSION

The main results in this study were first that our subjects' rate of ATP-turnover during the 10 s bicycling was around 2.7 times the rate corresponding to the maximal O_2 uptake. Glycolytic production of lactate was the most important source of energy, but aerobic ATP production and breakdown of phosphocreatine were also sig-

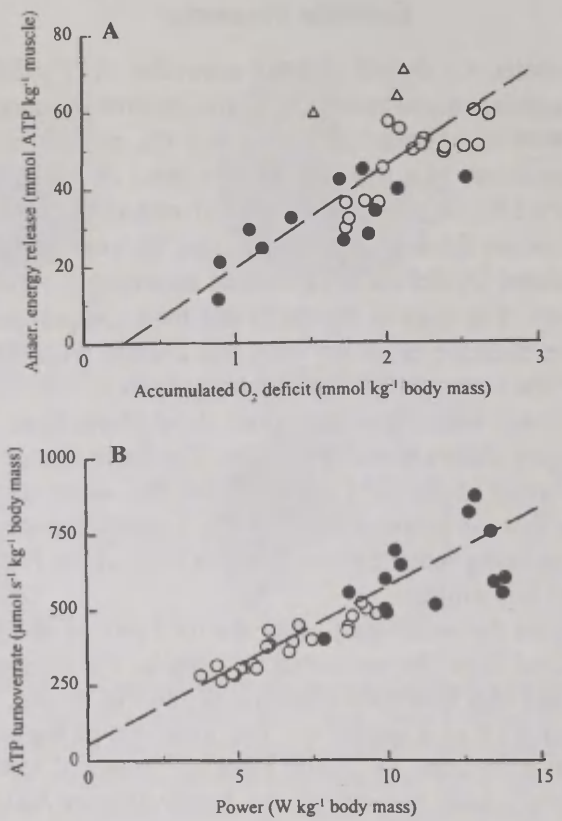

Figure 5. A, the accumulated O_2 deficit versus the anaerobic energy release in muscle. The dashed line is the expected relationship provided the biopsy data are representative of a working muscle mass equal to 25% of the body mass and that use of stored O_2 amounted to 0.25 mmol·kg^{-1} body mass as explained further in the method section. The data are from the present study (●) and from a former study with bicycling at 1.5 Hz to exhaustion (Ref 25, ○, Δ). Data from the subject deviating most from the line are shown by separate symbols (Δ).

B, the total ATP-turnover rate versus power. The data are from the present study (●) and from a former study with bicycling at 1.5 Hz to exhaustion (Ref 25, ○). The dashed line is a linear extrapolation of the subjects' relationship between the power and O_2 demand expressed as an ATP-turnover rate. The slope of 52 µmol·J^{-1} is the mean of the individual slopes and corresponds to a delta efficiency of 0.27 assuming ATP is produced by oxidation of glycogen. The line's Y-intercept of 55 µmol ATP s^{-1} kg^{-1} body mass is the weighed mean of all subjects' intercept in the two studies. The aerobic energy release was taken from the measured O_2 uptake plus an assumed use of stored O_2 of 0.25 mmol·kg^{-1} body mass, while the anaerobic energy release was taken from measured muscle metabolites assuming these values were representative of a working muscle mass of 25% of the body mass.

nificant. Finally, the rate of ATP-turnover seemed to increase linearly by the power, an observation compatible with the idea that the muscle economy during bicycling is constant and does not vary between moderate and very high powers.

Sources of energy during very intense exercise

Lactate production was the most important source of energy for both exercise. Even for the 10 s sprint did lactate production provide more than twice as much ATP as phosphocreatine breakdown did. Moreover, the mean rate of lactate production was 33% higher during the 10 s than during the 30 s exercise. These observations are not compatible with the idea that there is a considerable delay from the onset of exercise to the onset of lactate production and aerobic energy release. If stored ATP and phosphocreatine were the only sources of energy during the first seconds of exercise, the observed breakdown would have taken place in 2 s during the 10 s exercise. Our data on lactate's relative contribution to the anaerobic energy release are compatible with the idea that after a 1 s delay the anaerobic glycolysis provided 75% of the anaerobically produced ATP for the rest of the exercise in both the 10 and the 30 s exercises. The same relative contribution has been found for exhausting exercise lasting 30 s to 3 min [25]. Thus, our data suggest that if there is a delay from the onset of exercise to the onset of anaerobic glycolysis, the delay is at most around 1 s. That conclusion is also supported by data from several other studies using an all-out protocol [5, 10, 14–16]. The idea of phosphocreatine breakdown without simultaneous lactate production may thus have little physiologic significance.

All the data from the 30 s bout at a pedaling frequency of 2.0 Hz are similar to data on cycling at 1.5 Hz for 30 s to exhaustion [25]. Similar results were found by Jones *et al.* [16]. Comparison between two different studies using different pedaling frequencies seems therefore justified, for example in relation to Figure 4. Several former studies have examined the anaerobic energy release during all-out exercise of 6–30 s duration [5, 7, 10, 14–16, 26]. We

used exercise at a constant power and frequency and obtained similar data. Thus, all-out exercise and exercise at constant power seem to give similar results. None of the former studies have examined the importance of aerobic energy release in much detail.

The accumulated O_2 uptake rose linearly by the duration after an 8 s delay. O_2 is taken from the capillary blood and consumed in the working muscles, and consequently a large O_2 uptake through the mouth is not measured before venous blood with little O_2 reaches the lungs. It takes 6–10 s even during exercise for the blood to pass from the muscles' capillary bed to the lungs, and during this period 0.2–0.3 mmol O_2 kg^{-1} body mass is consumed during the exercise. Thus, our data suggest that the aerobic energy release starts with little if any delay at the onset of exercise. This conclusion is also supported by the high rate of aerobic ATP-production of 0.83 mmol ATP $s^{-1} \cdot kg^{-1}$ wet muscle mass, corresponding to around 80% of the rate when the subjects work at their maximal O_2 uptake. If the delay from the onset of exercise to the O_2 consumption increased was more than 2 s, aerobic processes would have provided ATP at a rate above that corresponding to the maximal O_2 uptake at later stages of the exercise to account for the O_2 consumption during the 10 s exercise. It should be noted that the aerobic energy release was calculated assuming that use stored O_2 amounted to 0.25 mmol $\cdot kg^{-1}$ body mass (similar to the negative of the Y-intercept in Figure 1); the basis for this value is given elsewhere [22, 24]. Consequently, our data suggest that aerobic processes provided one third of the total ATP-production for the 10 s exercises, and that is more than the contribution from phosphocreatine breakdown.

Exercise economy during very intense bicycling

The accumulated O_2 deficit is an entity calculated assuming a constant exercise economy independent of the exercise intensity [22, 24]. If the assumption is justified, the O_2 demand and entities derived from it can be estimated with little error. In our study the rate of ATP-turnover seemed to rise linearly by power, thus supporting

the assumption. However, it should be pointed out that our data for the highest powers were based on only seven subjects and that there were variations between the subjects. It cannot be ruled out that small nonlinear effects have been masked by this variation.

A constant economy independent of power or of how ATP is resynthesized was not unexpected. First, the myosin ATPase and other ATPases probably do not distinguish between ATP resynthesized by aerobic or anaerobic processes. In addition, it is conceivable that one ATP molecule can drive one crossbridge cycle and thus do a given amount of work whether the intensity is high or low. Our results nevertheless conflict conclusions drawn in several former studies where it was suggested that anaerobic energy release is only half as efficient as aerobic energy release [1, 12]. These studies quantified the anaerobic metabolism by the «O_2 debt» or enhanced postexercise O_2 consumption (EPOC). It is now well established that the EPOC overestimates the anaerobic energy release [2, 3, 24], perhaps because EPOC reflects the cost of restoring the body after exercise and not necessarily the anaerobic energy release itself during exercise. For example, lactate production is the main component of the anaerobic energy release [2, 3, 5, 7, 25, 26, 32], and during resting recovery after bicycling at least part of the lactate is resynthesized to glycogen [2, 13, 27]. While lactate production yields 3 ATP per glycosyl unit broken down from glycogen to lactate, the resynthesis of glycogen from lactate requires at least twice as much ATP. Thus, an EPOC more than twice as large as the accumulated O_2 deficit during exercise as observed by others [1–3] was not unexpected.

Type 2 or fast-twitch fibers may be little engaged at the onset of bicycling at moderate powers [11, 31], while type 2 fibers contribute more than type 1 or slow-twitch fibers during bicycling at high powers as judged from changes in the glycogen concentration of single muscle fibers [32]. It has been suggested that type 2 fibers work less economically than type 1 fibers [8]. That hypothesis would implicate a lower economy at the highest powers. This did not seem to be the case for our subjects, and our data are therefore compatible with the idea that the two main fiber types work with a similar economy during bicycling.

Assumptions for calculating the energy release

The anaerobic energy release should in principle be taken from changes in the lactate and phosphocreatine concentrations integrated over the whole body mass. As explained in the method section we used data on the muscle biopsies and assumed that these data represented a working muscle mass equal to 25% of the body mass. The true value most likely lies in the range 20–30% of the body mass. If our subjects' working muscle mass was 30% rather than 25% of the body mass, the calculated economy would be 11% less than the data in Figure 5b suggest. This means that moderate violations of the assumptions does not violate our conclusions.

We expressed the O_2 consumption in ATP-units assuming that 1 mol of O_2 used to oxidize glycogen gives 6.5 mol of ATP; a ratio that can be found in most textbooks of biochemistry. Bangsbo *et al.* [3] used on the other hand a ratio of 5.0 (according to the footing of Table 2 in Ref 3) or 4.6 (calculated from their accumulated O_2 deficit of 460 ml kg^{-1} muscle and the reported ATP-production of 94.7 mmol ATP kg^{-1} muscle given in their Table 2, and last paragraph of page 555 in Ref 3), and they obtained apparently excellent agreement between the anaerobic energy release obtained from measured metabolites in muscle and blood and indirectly by the accumulated O_2 deficit method (their reported difference is only 0.44%). If an ATP/O_2-ratio of 6.5 is used, a mismatch of more than 30% between these two entities is seen in their study. There are serious mechanical problems with the knee extensor model used since the work done may be roughly 40% larger than the recorded work (see Ref 21 for further details). Both errors are considerably larger than the random variation in our data (Figure 5, see also Figure 2 in Ref 25). Consequently, a roughly 40% error in the work done and a more than 30% error in converting the O_2 consumption to ATP-production may have led to their apparently nice match. We therefore doubt that the knee extensor model can be used for studies of the accumulated O_2 deficit.

Conclusions

Lactate production was the main source of energy for the 10 s exercises, but the contributions from aerobic processes and phosphocreatine breakdown were also significant. There was no detectable delay from the onset of exercise to the onset of lactate production and aerobic ATP-production. Our data support the idea that the exercise economy does not differ between low intensity exercise and exercise at intensities so high that exhaustion was reached in 10–30 s.

ACKNOWLEDGEMENTS

We are grateful to Bo Veiersted for medical assistance during the experiments, and to Bjørg I Selberg, Ada Ingvaldsen, Jorid T. Stuenæs, Astrid Bolling, and Per Holmstad for technical assistance.

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

ANALYSIS OF KINEMATIC, KINETIC AND ELECTROMYOGRAPHIC PARAMETERS OF THE SPRINTING STRIDE OF TOP FEMALE SPRINTERS

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ABSTRACT

The main purpose of this study was to find those kinematic, kinetic and electromyographic parameters of the sprinting stride that most affect maximal velocity of top female sprinters. A 20 m flying start test was made with a sample of four female sprinters of the Slovene national team, measuring besides maximal velocity also nine kinetic parameters in the contact phase of the sprinting stride with a Kistler force-plate. A 3-D APAS system (Ariel Performance Analysis System) was used to assess the kinematic parameters. An eight-channel telemetric electromyograph BIOTEL 88 (Glonner) was used to monitor the EMG activation of the leg muscles in the maximal velocity phase. We have found that the most important generators of maximal velocity are: duration of contact phase, duration of braking phase, minimal braking impulse, maximal impulse in propulsion phase, preserving maximal horizontal velocity of CG in braking phase and maximal grabbing velocity of foot in the forward contact phase. In light of the EMG activation, m. biceps femoris is one of the most important muscles in sprint.

Key words: sprint, maximal sprinting velocity, kinematics, kinetics, EMG activity, females

INTRODUCTION

The result in a sprint is generated by many biomechanic factors. Studies [3, 4, 7, 9, 12, 13, 16] show that the most important are: start reaction time, technique, electromyographic activity (EMG) of the muscles, production of force, neural factors, muscle structure; and some external factors, such as running surface, footwear and weather conditions. The efficiency of sprinting velocity depends on an optimal co-operation of four phases: starting-block phase, acceleration phase, maximal (constant) velocity phase and deceleration phase [13] . Maximal velocity is without doubt one of the most important factors of sprint, defined by the product of the stride length and the stride rate. These two are interrelated and dependent on morphologic characteristics, duration of the contact phase and force production in the braking phase and the propulsion phase [4, 9]. Electromyographic activity (EMG) of the leg muscles is, beside force production, also important for economy of sprinting. A common rule has been established that electromyographic activation of the lower extremities increases with running speed, this is especially true for the EMG activation prior- and during the braking phase in the contact phase [12, 15].

In this study we would like to establish those kinematic and kinetic characteristics of the sprinting stride and electromyographic parameters of muscle activation that generate maximal velocity in top female sprinters. The purpose is also, taking into account existing studies, to find whether biomechanic differences exist between male and female sprinters.

MATERIAL AND METHODS

The experiment included four top female sprinters of the Slovene national team. The average age of the subjects was 24.7 ± 4.1 years, average height 1.66 ± 0.04 m, average weight 57.2 ± 2.5 kg, average result on 100 m 11.53 ± 0.22 s and the best result on 100 m 11.30 s.

The measurements were performed on a track and field stadium with a tartan surface. Each subject performed two runs with maximal velocity over a distance of 45 m. There was a 8–10 min break between the runs. The better time was used. The athletes ran in sprinting shoes. The measurement system consisted of four units: a force-plate, APAS kinematic system, BIOTEL 88 — GLONNER electromyographic set and the AMES set for electronic measuring of running velocity. The dynamic parameters of the sprinting stride were registered with a KISTLER 9287 force-plate covered with a tartan layer and installed in the same plane as the track. Forces were measured in three directions on the force-plate, X-horizontal direction, Z — lateral direction and Y — vertical direction in the contact phase of the sprinting stride at maximal velocity. The sampling frequency was 2000 Hz.

For assessing kinematic parameters we used a video system for 3-D kinematic analysis ARIEL (Ariel Dynamics Inc., USA). The double sprinting stride was filmed in the phase of passing the force-plate with two synchronised SVHS video-cameras JVC TK-1281 EG, at 50 Hz frequency.

For analysis of the measured forces we used the package MATLAB (Mathworks Inc., USA). The following were computed: time of the contact of the foot with the force-plate (Tcon); time of braking (Tbrp); time of propulsion (Tprp) in the X — horizontal direction; maximal force (Fmax) in all three directions X, Y and Z; force impulse in the braking phase (Impb) and propulsion phase (Impa) — Figure 1. In the kinematic analysis process we digitised a 15-segment model of a body. The segments represent parts of the body connected with joints as points. The masses and centres of gravity of the segments and the common centre of gravity were computed according to the anthropometric model [6].

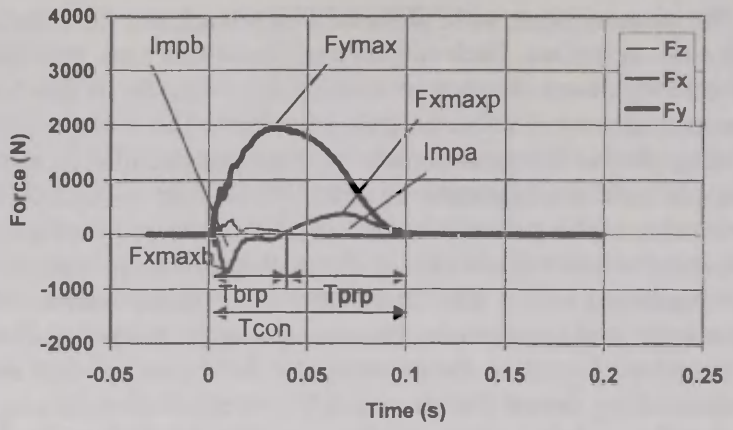

Figure 1. Force-time curves during the contact phase — Fz — force in lateral direction; Fx — force in horizontal direction; Fy — force in vertical direction; Tcon — contact time; Tbrp — time of braking; Tprp — time of propulsion; Fxmaxb — maximal force in horizontal direction (braking phase); Fxmaxp — maximal force in horizontal direction (propulsion phase); Fymax — maximal force in vertical direction; Fzmax — maximal force in lateral direction; Impb — force impulse in braking phase; Impa — force impulse in propulsion phase.

EMG was used to monitor muscle activation during the run. To record the EMG signals an eight-channel telemetric electromyograph BIOTEL 88 — Glonner was used. The measurements of the electrical muscular activation were made on muscles of the right leg: m. soleus (SOL), m. gastrocnemius (GAS), m. tibialis anterior (TA), m. vastus lateralis (VL), m. rectus femoris (RF) and m. biceps femoris (BF). Bi-polar silver-silver-chloride (AG-AgCl) electrodes with a diameter of 0.9 cm (Hellige) were used. The basic EMG signals were filtered with a high pass digital filter with a border frequency of 20 Hz.ed. The interval that began 200 ms before touch-down and ended 110 ms after touch-down was analysed (Figure 2). The interval was then divided into the pre-activation phase that began 200 ms before touch-down and lasted till touch-down and the contact phase that began at touch-down and lasted 110 ms.

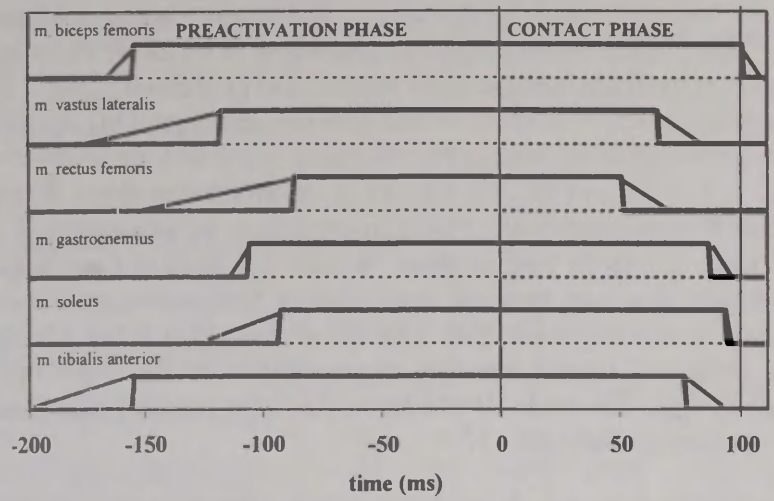

Figure 2. Electromyographic (EMG) muscle activity before and during the contact phase of the sprinting stride.

Statistical analysis of the analysed dynamic, kinematic and electromyographic parameters was performed with the SPSS statistical package.

RESULTS

The results in Table 1 show the basic characteristics of the kinematic, kinetic and electromyographic variables in conditions of maximal sprinting velocity. The maximal sprinting velocity of the subjects was 8.87 ± 0.14 $m \cdot s^{-1}$ with an average stride length of 1.98 ± 0.05 m, average stride rate 4.33 ± 0.20 Hz, average duration of contact phase 101 ± 0.05 ms and average duration of flight phase 137 ± 5.59 ms. The ratio between the braking and the propulsion phase, which defines the contact phase, is very important for an economic sprinting technique [9, 11, 12, 13]. The braking phase lasts 40 ± 0.03 ms and the propulsion phase 61 ± 0.02 ms. In the braking

phase the female sprinters develop on an average a horizontal force of -756 ± 143 N, in the propulsion phase it is 411 ± 29 N. The magnitude of the force impulse in the braking and propulsion phase is an important criterion of an economic sprinting technique [14]. Female sprinters achieve an average force impulse in the braking phase of -9.37 ± 1.23 Ns and 15.25 ± 1.34 Ns in the propulsion phase, which means that the production of force impulse in the propulsion phase is 1.6 times that in the braking phase. Besides the maximal force in the horizontal direction, maximal production of force in the vertical direction is also important. This is on the average 1924 ± 145.5 N for our sample of female sprinters, representing about 3.4 times their body weight. The medio-lateral force (Z) has relatively low values, on the average 234 ± 32.1 N.

Table 1. Kinematic, kinetic and EMG parameters of the sprinting stride

Variable	BA	BB	HA	PS	M	SD
Maximal velocity ($m \cdot s^{-1}$)	9,090	8,810	8,700	8,890	8,873	0,143
Stride length (m)	1,910	1,970	2,010	2,050	1,985	0,052
Stride frequency (Hz)	4,68	4,23	4,21	4,20	4,33	0,20
Angle of leg placement in braking phase (deg)	74,0	71,4	76,4	76,7	74,6	2,1
Push-off angle (deg)	60,0	66,9	66,5	69,8	65,8	3,5
Horizontal projection of CG in braking phase (m)	0,24	0,30	0,22	0,21	0,24	0,03
Horizontal projection of CG in prop. phase (m)	0,49	0,41	0,42	0,49	0,45	0,03
Horizontal velocity of CG in braking phase ($m \cdot s^{-1}$)	9,06	8,91	7,91	8,89	8,69	0,45
Horizontal velocity of CG in prop. phase ($m \cdot s^{-1}$)	9,24	8,94	8,13	8,91	8,80	0,41
Velocity of swing leg in braking phase ($m \cdot s^{-1}$)	14,54	14,38	13,59	13,89	14,10	0,38
Velocity of swing leg in prop. phase ($m \cdot s^{-1}$)	18,54	19,05	17,93	18,76	18,57	0,41
Grabing velocity of the foot ($m \cdot s^{-1}$)	5,60	6,24	5,51	4,44	5,44	0,64
Angular velocity of thigh in prop. phase ($deg \cdot s^{-1}$)	545,0	493,9	497,8	528,2	516,2	21,2
Contact phase (ms)	99	108	102	95	101	5
Flight phase (ms)	130	135	145	140	137	5
Braking phase (ms)	39	45	39	37	40	3

Variable	BA	BB	HA	PS	M	SD
Propulsion phase (ms)	60	63	63	58	61	2
Maximal force in X-horiz. direct. – prop. phase (N)	388	391	451	417	411	29
Maximal force in X-horiz. direct. – braking phase (N)	–693	–681	–681	–971	–756	143
Maximal force in Y-vertical direction (N)	1791	1938	1812	2157	1924	145
Maximal force in Z-lateral direction (N)	236	205	286	210	234	32
Force impulse in braking phase (N.s)	–7,480	–9,100	–10,700	–10,210	–9,373	1,237
Force impulse in propulsion phase (N.s)	14,038	15,250	16,700	15,930	15,480	0,978
EMG activity *m. tibialis anterior* PP (ms)	–200	–118	–98	–200	–154	46,5
EMG activity *m. soleus* PP (ms)	–40	–94	–127	–92	–88	31,1
EMG activity *m. gastrocnemius medialis* PP (ms)	–108	–102	–118	–97	–106	7,8
EMG activity *m. rectus femoris* PP (ms)	–200	–45	–46	–49	–85	66,4
EMG activity *m. vastus lateralis* PP (ms)	–200	–160	–49	–58	–117	64,9
EMG activity *m. biceps femoris* PP (ms)	–153	–155	–177	–154	–160	10,0
EMG activity *m. tibialis anterior* CP (ms)	50	85	85	84	76	15,0
EMG activity *m. soleus* CP (ms)	95	98	95	90	95	2,9
EMG activity *m. gastrocnemius medialis* CP (ms)	75	98	88	89	88	8,2
EMG activity *m. rectus femoris* CP (ms)	85	36	45	27	48	22,2
EMG activity *m. vastus lateralis* CP (ms)	64	42	54	96	64	20,0
EMG activity *m. biceps femoris* CP (ms)	102	96	87	107	98	7,4

Note: BA, BB, HA, PS — subjects; M — average; SD — standard deviation.

The horizontal velocity of the foot of the swing leg has a great influence on the magnitude of the horizontal velocity of the sprinter's CG during the contact phase. The average value of this parameter in the braking phase for female sprinters is 14.10 ± 0.38 m·s^{-1} and

in the propulsion phase 18.57 ± 0.41 $m \cdot s^{-1}$. The horizontal velocity of the foot therefore increases for 37.1% during the contact phase.

DISCUSSION

Some previous studies [9, 11, 12, 13] have established that the execution of the contact phase (Figure 1) represents one of the most important generators of maximal sprinting velocity efficiency. The contact phase should be as brief as possible and the horizontal force in the propulsion phase developed by the sprinter as large as possible. The sprinters in our sample have an average duration of the contact phase of 101 ms. Top sprinters that develop maximal velocity from 10.20 to 11.60 $m \cdot s^{-1}$ have a contact phase between 85 and 95 ms [3]. The athlete BA who achieved the highest maximal velocity of 9.09 $m \cdot s^{-1}$ in the experiment also has the shortest contact phase of 99 ms. The ratio between the duration of the braking phase and the propulsion phase is 40% : 60%, which is from the viewpoint of economy [11, 13] a very good indicator of a rational technique of maximal sprinting velocity. The braking horizontal force and the braking time that define the braking impulse should be as small as possible so that there is the least possible drop in horizontal velocity of CG in the first part of the contact phase. In our sample the average horizontal velocity decreases for 1.4% in the braking phase, showing a very economic execution of the sprinting stride. Research made on samples of sprinters [11, 13] shows that the drop in velocity in the braking phase varies between 3.1% and 4.8%.

Female sprinters develop in the propulsion phase on an average a force impulse 1.63 times greater than in the braking phase. The most favourable ratio (1:1.75) of the force impulse in the braking phase and the propulsion phase had the fastest subject BA. Vertical forces have much greater values than the horizontal forces in the contact phase. Maximal vertical force varies in female sprinters between 1791 N and 2157 N, representing 3.2 to 3.7 times their body weight. A general tendency exists that both forces in the hori-

zontal as well as in the vertical direction increase with velocity [12]. Male sprinters who achieved a maximal velocity between 11.12 $m \cdot s^{-1}$ and 11.45 $m \cdot s^{-1}$ had maximal vertical force up to 4.6 times their body weight [16]. The economics of the sprinting technique is connected with the magnitude of vertical forces, especially from the viewpoint of vertical oscillations of the body centre of gravity. A hypothesis exists that vertical oscillations are smaller in biomechanically more economic running [4, 13]. This hypothesis can be also confirmed with a rather high certainty on the basis of the results of the sprinters in our sample, where the average of vertical oscillations of the body centre of gravity was 5.8 cm. The fastest sprinter's BA average was 4.6 cm and the slowest HA 8.5 cm.

An important role in the economy of locomotion in sprint running goes to the parameter velocity of movement of the swing leg [7, 9, 16]. It is important to ensure a high horizontal velocity of the foot of the swing leg in the contact phase for an efficient sprinting stride and also as great as possible "grabbing" velocity of the foot in the front contact phase. The swing leg (thigh-shank-foot) is the only segment in the braking phase that produces propulsive force in the forward direction [14]. The average horizontal velocity of the foot of the sprinters in the braking phase in our experiment was 14.10 ± 0.38 $m \cdot s^{-1}$ and increased in the propulsion phase on an average by 4.47 $m \cdot s^{-1}$. It was the fastest sprinter BA that has the highest horizontal velocity of the foot of the swing leg in the braking phase — 14.54 $m \cdot s^{-1}$. The athlete PS had the greatest absolute increase in the horizontal velocity of the foot of the swing leg in the contact phase — 4.87 $m \cdot s^{-1}$ — who achieved the second best result in the maximal sprinting velocity criterion. We therefore find that in the propulsion phase for female sprinters the horizontal velocity of the foot is 2.11 times greater than the horizontal velocity of CG. The horizontal velocity of the foot parameter [9] shows the importance of the swing leg function, which contributes an important part to the take-off force impulse in the horizontal direction in the contact phase.

One of the key problems of the biomechanics of sprinting is how to ensure the most economic phase of the forward contact so that the loss in horizontal velocity of CG is the smallest possible. This is possible with a high grabbing velocity of the foot backwards under the CG of the body [9]. The average grabbing velocity just before contact in the forward contact phase is 5.45 ± 0.65 m·s^{-1} for female sprinters.

A high grabbing velocity is ensured by the parameter back-swing-velocity, generated mostly by the iscio-crural muscles [16]. There is a high positive correlation ($r = 0.78$) between the velocity of hip extension in the contact phase and maximal sprinting velocity in male sprinters [7]. Top sprinters manage to achieve an angular back-swing-velocity of up to 800 deg·s^{-1}. A research [16] shows that sprinters with a maximal sprinting velocity between 10.30 and 10.60 m·s^{-1} achieve maximal angular back-swing-velocities between 500 and 600 deg·s^{-1}. Female sprinters in our experimental group have on an average a velocity of 516 ± 21.2 deg·s^{-1}. On the basis of the results of our study we can see a general tendency that female athletes who have achieved better results in maximal sprinting velocity also have a higher back-swing-velocity.

The co-ordination of electrical muscle activation is very important in order to explain the kinematic and kinetic characteristics of the sprinting stride (Figure 3). Electrical muscle activation begins even before contact with the ground. Some muscles take care of the forward swing of the leg and some are getting ready for the contact of the foot with the ground.

The first part of the swing-leg movement happens without electrical activation of the hamstring muscles, m. gluteus maximus and m. gastrocnemius [15]. It is therefore possible to conclude that this part of the swing is caused by outside forces, for example force of the reaction of the ground at the moment of take-off. Electrical activity of the above-mentioned muscles begins approximately 210 ms before the contact phase [15], leading to the conclusion that these muscles are more concerned with braking the swing leg at the end of the swing than with active pulling of the swing leg forward. We only monitored *m. gastrocnemius* and *m. biceps femoris* in our

study. Electrical activity of *biceps femoris* began on an average 155 ms before the contact phase, for *m. gastrocnemius* it was 106 ms.

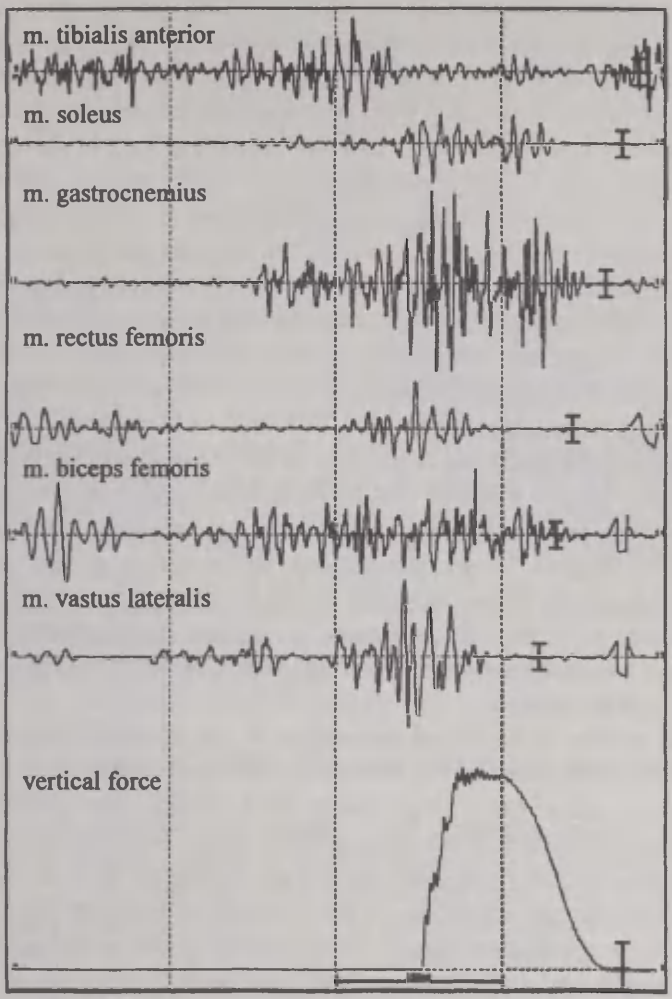

Figure 3. Raw electromyographs of selected muscles during stride of 1 subject (BB), shown together woth ground reaction force.

The subjects differed in the activity of *m. rectus femoris*. *M. rectus femoris* was active during the whole pre-activation phase in one subject, in the remaining three it was active in two intervals. For the latter, the first interval ended on an average 135 ms before the contact phase and the second started 49 ms before the contact phase. In sprint the electrical activation of the shank muscles begins 120 to 180 ms before the contact of the foot with the ground [5, 15]. For our subjects the electrical activation of the muscle *m. tibialis* began on the average 155 ms before the start of the contact phase. The modulation of the muscles *m. soleus* and *m. gastrocnemius* is different. The electrical activation of *m. soleus* began on the average 93 ms before the start of the contact phase and in average 106 ms for the *m. gastrocnemius*. These two times are shorter than given by other authors [5, 15], but still longer than the electromechanic delay for which they give a duration between 20 and 100 ms [8]. So there is still enough time to increase the stiffness of the muscle to an adequate level.

Unexpected electrical activation of m. tibialis was measured in the contact phase. It is true that its electrical activity was noticeably smaller than before the beginning of the contact phase, however, it would be logical for *m. tibialis* not to be active in the contact phase. *M. tibialis* is an antagonist in the contact phase and does not contribute to better amortisation or greater acceleration. Other authors [15] state that *m. tibialis* does not show electrical activation in the contact phase.

The results of electrical activation of the muscles showed that the electrical activity of the muscles ceases before toe-off, i.e. even before the end of the contact phase. Such results were obtained by Simonsen, Thomsen & Klausen [15] for sprint and Brandell [2] for slow running. They suppose that the mechanics of delay is the reason that electrical activation of the muscles ends before the end of the contact phase. Mechanical delay is due to the relaxing time of the muscles. *M. adductor pollicis* has a half relaxing time of 47.3 ms ± 4.9 ms and about 200 ms to full relaxation [1]. For our subjects electrical activity of most muscles ended a little before toe-off. This is somewhat later than given by Simonsen, Thomsen & Klausen [15]. An exception is *m. vastus lateralis*, its electrical

activity ends as given by the previously cited work. Electrical activity of *rectus femoris* lasted to about half the contact phase, which is similar as for one subject in a study by Simonsen, Thomsen & Klausen [15]. In the contact phase, *m. biceps femoris* was activated longest and its electrical activity lasts on an average 101ms after touchdown. *M. biceps femoris* is one of the most important muscles in sprint, as was also confirmed in this study.

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

COMPARISON OF TWITCH CONTRACTILE PROPERTIES OF PLANTARFLEXOR MUSCLES IN YOUNG AND MIDDLE-AGED MEN

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ABSTRACT

This study compared twitch contractile properties of plantarflexor muscles in resting and post-activation potentiation state between the groups of young (19- to 22-year-olds, n = 9) and middle-aged (45- to 55-year-olds, n = 9) men. The posterior tibial nerve in popliteal fossa was stimulated supramaximally by square wave pulses 1 ms duration. Contractile measures included isometric twitch maximal force, post-activation potentiation, ratio of twitch to maximal voluntary contraction (MVC) force and twitch contraction and half-relaxation time. The young men had significantly higher MVC force and post-activation potentiation value compared to middle-aged men. There were no significant differences in twitch maximal force in resting and potentiated state between the subject groups. Potentiated twitch maximal force and potentiated twitch maximal force/MVC force ratio were significantly higher compared with resting twitch for young men. The resting twitch maximal force/MVC force ratio was higher in middle-aged men. The resting and potentiated twitch contraction time and potentiated twitch half-relaxation time in young men were significantly shorter compared to middle-aged men. Potentiated twitch contraction time was significantly shorter compared with resting twitch also for young men. It is concluded that middle age is characterized by reduced capacity for force potentiation and slowed muscle contraction. However, the force-generating capacity of middleaged muscles seems to be unchanged compared to young adults.

Key words: human plantarflexor muscles, contractile properties, twitch potentiation, aging

INTRODUCTION

The aging process has been shown to lead to both structural and functional changes in the neuromuscular system. Reduced strength and contraction speed are two main characteristics of performance in aging muscle [1, 8, 15]. There have been numerous studies assessing the effect of aging to voluntary muscle strength. Some authors have suggested a relative constant annual loss of strength. However, most authors have suggested that there is apparently a plateau of muscle strength until the mid-40s, after which there is an accelerated loss of strength and speed of movements [11, 14, 15, 17, 19]. Less attention has been paid to study the influence of aging to the electrically evoked twitch contractile properties of human skeletal muscles which can be used for measuring neuromuscular performance independently from skill and motivation. A prolongation of twitch contraction time and half-relaxation time [5, 8, 17, 22] and reduction of the twitch post-activation potentiation [9, 17, 18, 22] have been reported in elderly muscles compared to young adults, yet it is not clear at which ages this impairment begins. The changes in electrically evoked twitch contractile properties in middle-aged subjects are not well established.

The purpose of the present study was to compare the twitch contractile properties of skeletal muscles in resting and post-activation potentiation condition in young and middle-aged men. Recordings were performed from the plantarflexor muscles which are important in posture and movement and are involved in many working and sport activities.

MATERIAL AND METHODS

Subjects

Two groups of moderately physically active men were studied: young (19–22 years, n = 9) and middle-aged (45–55 years, n = 9). The mean age, height and weight of the subjects are shown in Ta-

ble 1. The subjects were screened by questionnaire to exclude those with diagnosed neuromuscular disorders. All the subjects were informed of the procedures to be utilized as well as the purpose of the study and their written informed consent was obtained. The study carried the approval of the Ethics Committee of University of Tartu.

Table 1. Mean (±SEM) age and anthropometric characteristics of subject groups

Age group	Variables		
	Age (yr)	Height (cm)	Body mass (kg)
19–25 yr, n = 9	20.3 ± 0.4*	183.6 ± 2.7*	83.3 ± 5.5
45–55 yr, n = 9	50.8 ± 2.1	175.4 ± 1.6	87.4 ± 5.3

* $p < 0.05$ compared to middle-aged subjects

Apparatus and Experimental Procedure

The subjects were seated in a specially designed dynamometric chair with the dominant leg (usually the right) flexed to 90° at the knee angle and mounted inside a metal frame. The foot was strapped to on aluminium footplate. The inclination of the foot could be altered by rotating the footplate about on axis that corresponded to that of the ankle joint. The axis of rotation approximately alignated with the tip of the medial malleolus and the ankle was dorsiflexed to 20°. The kneecap and front side of the thigh were held down by a adjustable pad. Torques acting on the footplate were sensed by strain-gauge transducer connected with the footplate by rigid bar. Signals from the strain-gauge transducers were linear from 10–1600 N. The point of application of force to footplate located on articulation regions between metatarsus and ossa digitorum pedis. The force signals were sampled at a frequency of 1 kHz and digitized signals were stored on a hard disk.

During the recording of maximal voluntary isometric contractions (MVC) of the plantarflexor muscles the subjects were instructed to push the footplate as strongly as possible for 2–3 s.

Verbal encouragement and visual feedback were used to motivate the subjects. The greatest force of the three maximal efforts was taken as MVC force. A rest period of 2 min was allowed before and between each of the three attempts.

To determine the contractile properties of the plantarflexor muscles during an isometric twitch, the posterior tibial nerve was stimulated through a pair of surface carbon-rubber electrodes (Nemectron, Germany). The cathode (2 × 4 cm) was placed over the tibial nerve in popliteal fossa and anode (7 × 12.5 cm) was placed under the posterior-medial side of the thigh. Supramaximal square wave pulses of 1 ms duration were delivered from an isolated voltage stimulator Medicor MG-440 (Budapest, Hungary). The evoked compound action potential (M-wave) of the soleus muscle was recorded using bipolar (20 mm interelectrode distance) EMG electrodes (Beckman miniature skin electrodes). The electrodes were placed longitudinally on the motor point area of the soleus muscle determinated by electrical stimulation. As reference electrode, a large carbon rubber plate (Nemectron, 7 × 12.5 cm) was placed over the proximal part of the triceps surae muscle between the stimulating and recording electrodes. EMG signals were amplified and displayed using standard Medicor MG-440 (Budapest, Hungary) preamplifier with frequency band ranging from 1 to 1 kHz. These signals were sampled at a frequency of 1 kHz. During isometric twitch recording the stimulus intensity varied from approximately 25 V to supramaximal in increments of 30% to 50% (130–150 V). Simple stimuli were given at 30 s intervals and the voltage was increased in increments of 20 to 25 V until supramaximal twitches were reached. The maximal amplitude of the M-wave was used as a criterion for determining the supramaximal stimulus intensity.

Supramaximal isometric twitches of the plantarflexor muscles were elicited after the subject had rested for 5 min. After the resting twitches had been recorded the subjects were instructed to make a MVC for 5 s and then relax. A potentiated (post-activation) twitch was elicited within 1 s after the onset of relaxation. Twitch maximal force (F_{max}) — the highest value of isometric force production, contraction time (CT) — the time to maximal twitch force, half-relaxation time (HRT) — the time of half of the decline in

maximal twitch force in resting and potentiated condition were calculated. The percentage increase in potentiated twitch maximal force in relation to resting twitch maximal force was taken as an indicator of the post-activation potentiation (PAP). Maximal twitch force was expressed as a percentage of maximal voluntary contraction force (F_{max}/MVC). The sequence of the tests was: resting twitch, potentiated twitch and MVC force.

Data Analysis

Data are means and standard errors (±SEM). One-way analysis of variance (ANOVA) following by Scheffe post hoc comparisons were used to test for differences between groups. A level of $p < 0.05$ was selected to indicate statistical significance.

RESULTS

A significantly higher mean MVC force and post-activation potentiation values were found for young men compared to middle-aged men (Figure 1). Potentiated twitch maximal force and potentiated twitch maximal force/MVC force ratio were significantly higher compared with resting twitch only for young men (Figure 2). There were no significant differences in twitch maximal force in resting and potentiated state between the subject groups. The middle-aged subjects had the greater mean value of resting twitch maximal force/MVC force ratio than young subjects. The potentiated twitch contraction time was significantly shorter compared with resting twitch for young men (Figure 3, left). No significant differences in twitch half-relaxation time in either resting and potentiated state was found (Figure 3, right). Young men had significantly shorter mean values of resting and potentiated twitch contraction time and potentiated twitch half-relaxation time than middle-aged men.

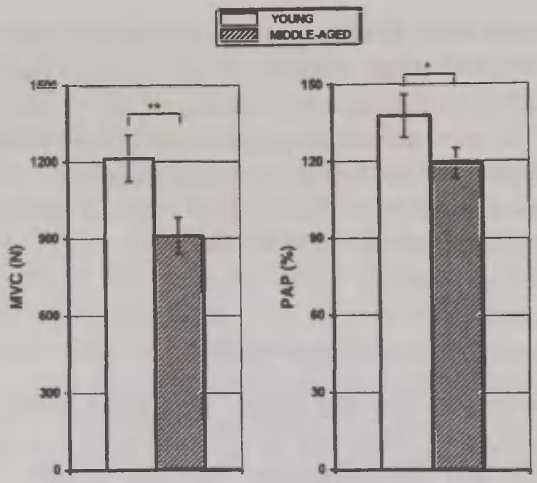

Figure 1. Mean (±SEM) values of maximal voluntary isometric contraction (MVC) force (*left*) and post-activation potentiation (PAP, *right*) in young and middle-aged men. * $p < 0.05$; ** $p < 0.01$.

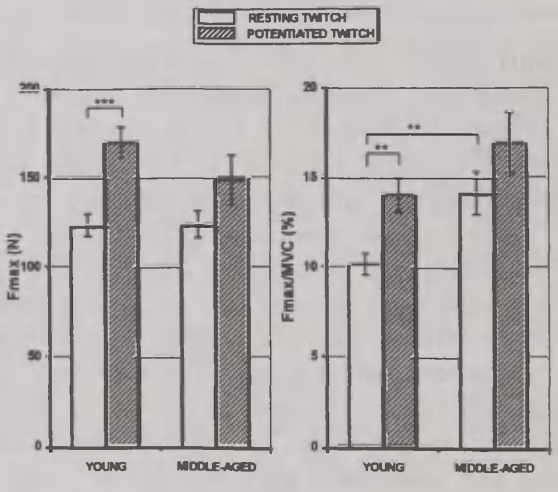

Figure 2. Mean (±SEM) values of twitch maximal force (F_{max}, *left*) and ratio of maximal twitch to maximal voluntary contraction force (F_{max}/MVC force, *right*) in young and middle-aged men.
** $p < 0.01$; *** $p < 0.001$.

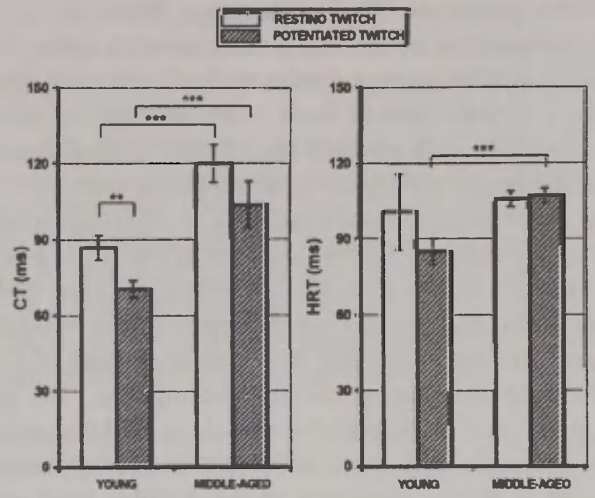

Figure 3. Mean (± SEM) values of twitch contraction time (CT, *left*) and half-relaxation time (HRT, *right*) in young and middle-aged men.
** $p < 0.01$; *** $p < 0.001$.

DISCUSSION

The main finding of the present study is that middle-aged individuals had reduced MVC force and twitch potentiation capacity and prolonged twitch contraction time of plantarflexor muscles compared to young men. The decrease in MVC force in plantarflexor muscles in middle age has also been found by Fugl-Meyer *et al.* [10] and Belanger *et al.* [2]. However, it is interesting to note that significant decline in MVC force began earlier than reported by many investigators. The reduction of twitch potentiation and prolongation of contraction time in middle-aged plantarflexor muscles are consistent with report of Vandervoort and McComas [22]. These changes migh have been due to an increase in the proportion of tension developed by the type I (slow-twitch) muscle fibres, stemming from the loss or reduction in size (atrophy) of type II (fast-twitch) fibres [4, 16, 20]. It can be assumed that mainly the

type II fibres potentiate [3, 7]. However, there are no data on change in composition of the ankle muscles with aging. Further, if this explanation were correct, both maximal voluntary and electrically evoked torques should have been reduced in middle-aged subjects. Our data indicated no significant differences in twitch maximal force between middle-aged and young men.

Several other factors could contribute to the reduced twitch potentiation and prolonged contraction time in resting and potentiated state and half-relaxation time in potentiated state in middle-aged muscle. Structure and function of the sarcoplasmic reticulum (SR) may change with age [21], thus influencing amount of Ca^{2+} available to the contractile apparatus for potentiation. The prolonged half-relaxation time of potentiated twitch in middle-aged muscles is also one indicator of reduced efficiency in SR function. Another possibility of a change mediated at the cellular level with aging could be in regard to the binding of Ca^{2+} to myosin [6]. It has been shown that myosin becomes phosphorilated during repetitive contractions and in this state is more receptive to Ca^{2+} activation [13]. Age-related change in phosphorylating capacity of the myosin light chain in fast twitch muscle fibres may be one cause of decrease of the ability to generate force rapidly [12]. An additional factor which may influence contractile properties of middle-aged muscle is the series elastic component of muscle.

Our data indicated that middle-aged subjects have significantly higher twitch maximal force/MVC force ratio compared to young subjects. Since it appeared to be caused first of all by the decline in MVC force, it could indicate the reduction of motor unit activation with increasing age. An age-related decrease of habitual activity could contribute to a loss of voluntary muscle strength through a deterioration of recruitment pattern [1].

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

ANALYSIS OF THE STRUCTURE OF COMPETITIVE SUCCESSFULNESS IN BIATHLON

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ABSTRACT

On a sample of 89 participants of the 20 km individual competition at the World Championship in biathlon we analysed the structure of competitive successfulness, represented by three components: net ski-running time, shooting time and precision of shooting. Analysis of the sample showed great differences in quality between the individual competitors. A t-test for small independent samples showed statistically significant differences ($p < 0.05$) between the best ten and the last ten ranked competitors in all the components of competitive successfulness. Statistically significant ($p < 0.05$) correlations were obtained between the precision of shooting, net running time and shooting time. Factor analysis gave a two-component latent structure of competitive successfulness. The first main factor (39.3% of Var.) was mainly dominated by the projections of the net running times. The second factor (14.3% of Var.) had the highest projections with the variables shooting time and shooting precision. After an oblique rotation, it emerged that the two factors significantly correlated ($r = -0.32$, $p < 0.05$). By using regression analysis it was found that the greatest part of successfulness could be attributed to the shooting component — number of hits — (50%), somewhat less (45%) to the net running time component and the remainder of 5% to shooting time component.

Key words: biathlon, world championship, 20 km individual competition, competitive successfulness

INTRODUCTION

Biathlon is a winter sport, where athletes compete separately by gender and in five disciplines, one of these is the 20 km distance. This is the longest distance for males and is run in five circles of 3.5 to 4.5 km with four shootings. The shooting positions are in the following sequence: lying down, standing, lying down and standing [6].

Nitzsche [4] presented a model of competitive successfulness, where the end result depends on the achievement in ski-running and achievement in shooting. Successfulness in running is defined by the running time, while for shooting there are two: shooting time and precision of shooting. It follows from this model that the result in biathlon depends on the sum of net running time, shooting time and the time penalties for missed shots and can be formulated as a simple sum, as follows:

Result in biathlon = running time + shooting time + time penalties for missed shots.

The result in biathlon, from a narrow competitive viewpoint, really is a simple mathematical function and a very simple mathematical model. However, for the needs of theory of sports training, the question on the relative contribution of the individual components of successfulness is much more important — this can be ascertained by using a stochastic regression model. In this model we can represent the result as a weighted function of the individual components of successfulness, mirroring the actual competitive abilities of the competitors in biathlon.

Result = (b1 × running time) + (b2 × shooting time) + (b3 × time penalties)

What has been written for the final sub-criteria (= components) of successfulness is valid also for their sub-components. The end time is therefore obtained as a sum of the times in the five circles, end shooting time as a sum of the four shooting times and the final number of missed shots as a sum of the shots missed at the individual four shootings.

The basic hypothesis of our study is that the competitive result is equally defined by the net running time and the successfulness of shooting — composed of shooting time and number of hits. Because of the supposition of an independence of the successfulness components the partial relative contributions of the two components should also be equal or at least similar.

It is very important for the coaches in biathlon, from the training point of view, to know the shares the individual components contribute to the end result, since each component demands different abilities from the athlete [4], ranging from typical ski-running to typical shooting abilities. The bridge between them is, according to Nitzche [4], the abilities for an efficient shooting preparation.

The art of achieving top competitive results in biathlon hides mostly in such a system of athletes' preparation, which enables simultaneous rise of abilities both in ski-running as well as shooting, at the same time we must not forget the abilities for an efficient shooting preparation. To be successful in competition therefore means as short as possible (= optimal) running time, as short as possible (= optimal) shooting time and the best possible shooting (= if possible without misses). A rather tough problem, from the viewpoint of successfulness and training, is the question of reference of the relations between the individual factors of successfulness and the question of correlation of these factors with successfulness. These two are precisely the subject and problem of this study, in which we would like to verify the hypothesis that no statistically significant correlation between the individual factors of successfulness in biathlon exists and that the contribution of each to the final result is statistical significant.

The main aim of this study was to ascertain the manifest and latent structure of the relations between the three essential factors of competitive successfulness of top competitors in biathlon.

1. The ski-running time — TEK: a sum of the achieved times in the five circles of the competitive 20 km distance (TEK1, TEK2, TEK3, TEK4, TEK5),

2. shooting time — STR: a sum of the four shooting times (STR1, STR2, STR3, STR4), two of these in the prone position (first and third shooting) and two standing up (second and fourth),
3. number of hits — ZAD (each miss means a time penalty of one minute): a sum of the missed shots at the four individual shootings (ZAD1, ZAD2, ZAD3, ZAD4).

It was also the aim of this study to ascertain the level of correlation between the individual factors of successfulness and the final result in biathlon (REZUL). Here we shall also find the contribution (beta, % of Var.) the individual factors have in defining successfulness, without regard to the level of the defined successfulness sub-criteria.

METHODS

The analysis of competitive successfulness was performed on a sample of top competitors, which competed in 1997 at the World Championship [7, 2] in Osrblie (Slovakia).

The difference in quality between the groups of the first ten (BEST — B) and the lowest ten (LOW — L) was tested with t-test for small independent samples for all components of successfulness.

Linear correlation (first phase) and factor analysis (oblimin rotation, second phase) were used to find the referential manifest and latent structure of the model of competitive successfulness.

The level of connection between the individual factors of successfulness and the final result in biathlon was analysed with linear correlation. The shares of explained variance of successfulness (beta, % of Var.) that the individual predictors contribute were found by linear regression analysis.

RESULTS

Table 1 shows the results of testing (with t-test) differences between the group of ten best and ten lowest placed at the 20 km biathlon competition at the 1997 World Championship.

Table 1. Results of t-test, (BEST — B, n = 10), (LOW — L, n = 10)

Variable	Unit	Group	X	S.D.	Sig. T
Shooting time — STR	1/10 sec.	B	1334	120.76	0.00
		L	1667	226.82	
1. shooting time — STR1	Sec.	B	35.6	4.20	0.00
		L	44.1	5.65	
2. shooting time — STR2	Sec.	B	31.6	4.35	0.00
		L	41.1	7.62	
3. shooting time — STR3	Sec.	B	36.7	3.89	0.00
		L	44.7	7.41	
4. shooting time — STR4	Sec.	B	29.5	3.41	0.02
		L	36.5	7.40	
Ski running time TEK	1/10 sec.	B	30114.80	783.08	0.00
		L	32239.10	642.06	
Ski running time — 1. circle TEK1	1/10 sec.	B	6012.00	180.48	0.00
		L	6360.00	117.95	
Ski running time — 2. circle TEK2	1/10 sec.	B	5516.00	120.85	0.00
		L	5818.00	153.90	
Ski running time — 3. circle TEK3	1/10 sec.	B	6323.00	160.90	0.00
		L	6845.00	211.94	
Ski running time — 4. circle TEK 4	1/10 sec.	B	5642.00	170.74	0.00
		L	6063.00	200.28	
Ski running time — 5. circle TEK5	1/10 sec.	B	6621.80	199.27	0.00
		L	7153.10	182.49	
Hits all together ZAD	n	B	18.80	1.03	0.00
		L	14.10	1.37	
Hits in 1. shooting ZAD1	n	B	4.70	0.48	0.02
		L	4.00	0.66	

Variable	Unit	Group	X	S.D.	Sig. T
Hits in 2. shooting	n	B	4.80	0.42	0.01
ZAD2		L	3.60	1.08	
Hits in 3. shooting	n	B	4.60	0.70	0.05
ZAD3		L	3.30	1.06	
Hits in 4. shooting	n	B	4.70	0.48	0.00
ZAD4		L	3.20	0.92	

Analysis of the differences between the ten best (B) and ten lowest (L) ranked competitors, using t-test for small independent samples and 5% error level, showed statistical significance for all the variables of the model of competitive of successfulness in biathlon.

Table 2 shows that all the correlation coefficients between the basic components of successfulness at the competition in biathlon are statistically significant ($p < 0.05$).

Table 2. Matrix of correlation coefficients between shooting time (STR), running time (TEK) and precision of shooting measured in hits (ZAD)

	STR	TEK	ZAD
STR	1.00		
TEK	0.27**	1.00	
ZAD	–0.31**	–0.23*	1.00

* $p < 0.05$ ** $p < 0.01$.

The presented correlation coefficients in Table 2 show a significant correlation ($r = –0.31$) between the shooting time (STR) and number of hits (ZAD). It can be seen that the correlation is negative, therefore longer shooting time means in general a lower number of hits. The correlation between the net running time (TEK) and shooting time (STR) is positive ($r = 0.27$), which means that faster ski-runners in general used less time for shooting. The correlation ($r = –0.23$) between the number of hits (ZAD) and net running time (TEK) was also statistically significant.

The correlations between the elementary variables of the components of successfulness in biathlon are shown in Tables 3, 4, 5 and 6.

Table 3 shows the correlations between the shooting time variables. The highest correlation (r = 0.51) was obtained between the first and the third shooting time (in prone position). The second coefficient in magnitude (r = 0.45) shows the statistically significant ($p < 0.01$) between both shooting times in standing position. The correlation relationship between the first shooting time (STR1) and the fourth (STR4) was completely non-significant (r = 0.08). The obtained correlation coefficients suggest a hypothesis on statistically significant correlation between shooting times, especially for equal shooting position.

Table 3. Matrix of inter-correlation coefficients between shooting times

	STR1	STR2	STR3	STR4
STR1	1.00			
STR2	0.35**	1.00		
STR3	0.51**	0.40**	1.00	
STR4	0.08	0.45**	0.22*	1.00

* $p < 0.05$ ** < 0.01.

Table 4. Matrix of coefficients of correlation between variables showing hits (ZAD)

	ZAD1	ZAD2	ZAD3	ZAD4
ZAD1	1.00			
ZAD2	–0.05	1.00		
ZAD3	0.17	0.13	1.00	
ZAD4	–0.04	0.15	–0.03	1.00

On the basis of the obtained values a supposition on a relatively high independence between the individual shootings could be made. However, a completely different picture was obtained for the correlations between the net running times in the individual circles (Table 5).

All the correlation coefficients between the variables of running times (TEK) were statistically significant ($p < 0.01$) and ranged from medium high values (r = 0.74) to high values (r = 0.89). Since the differences in correlation are relatively small we could suppose

the existence of a high general correlation between running times, that is a high reliability of expressing ski-running capability.

Table 5. Matrix of correlation coefficients between circle running times

	TEK1	TEK2	TEK3	TEK4	TEK5
TEK1	1.00				
TEK2	0.79**	1.00			
TEK3	0.77**	0.87**	1.00		
TEK4	0.74**	0.83**	0.86**	1.00	
TEK5	0.75**	0.80**	0.89**	0.80**	1.00

** $p < 0.01$.

Table 6. Matrix of coefficients of cross-correlation between variables of running times (TEK) in circles, shooting times (STR) and variables showing number of hits (ZAD)

	STR1	STR2	STR3	STR4	ZAD1	ZAD2	ZAD3	ZAD4
TEK1	0.29**	0.20	0.20	0.12	–0.08	–0.05	–0.15	–0.22*
TEK2	0.23*	0.22*	0.12	0.19	–0.14	0.01	–0.13	–0.22*
TEK3	0.28**	0.15	0.13	0.19	–0.14	0.04	–0.12	–0.21
TEK4	0.31**	0.19	0.13	0.08	–0.06	0.09	–0.16	–0.13
TEK5	0.31**	0.07	0.12	0.12	–0.10	0.00	–0.11	–0.23*
ZAD1	0.28**	–0.03	–0.03	0.00				
ZAD2	–0.16	–0.33**	–0.10	0.06				
ZAD3	–0.18	–0.03	–0.31**	0.17				
ZAD4	–0.14	–0.24*	–0.22*	–0.22*				

* $p < 0.05$ ** $p < 0.01$.

An inspection of Table **6**, which shows the cross-correlation coefficients between the elementary variables of successfulness in biathlon, shows the highest correlation ($r = -0.33$) between the shooting time in standing position and the number of hits in the same. In general, at the second shooting, the competitors that used less time were also more successful. The correlation coefficients between variables of running times in the individual circles and the shooting times ranged from completely insignificant ($r = 0.07$) to low average values ($r = 0.31$). The highest correlations were obtained mostly between the first shooting time and the running times in all five circles.

The latent structure of the elementary variables of successfulness was ascertained with the help of factor analysis. The PB (Stalec-Momirovic) criterion extracted two significant factors. The first factor explained the greatest part of common variance (39.3%) of the system of manifest variables (Table 7) and the second factor 14.3%.

Table 7. Factor analysis of variables of successfulness in biathlon (after oblique rotation with Oblimin method and Kaiser normalisation)

Variable		FAC1	FAC2
Result	— REZUL	0.80	–0.72
Running time in 10. circle	— TEK1	0.87	–0.33
Running time in 20. circle	— TEK2	0.93	–0.29
Running time in 30. circle	— TEK3	0.95	–0.27
Running time in 40. circle	— TEK4	0.91	–0.29
Running time in 50. circle	— TEK5	0.92	–0.24
Time of 10. shooting	— TSTR1	0.33	–0.66
Time of 20. shooting	— TSTR2	0.16	–0.74
Time of 30. shooting	— TSTR3	0.15	–0.72
Time of 40. shooting	— TSTR4	0.14	–0.38
Hits in 10. shooting	— ZAD1	–0.17	0.20
Hits in 20. shooting	— ZAD2	–0.01	0.49
Hits in 30. shooting	— ZAD3	–0.19	0.35
Hits in 40. shooting	— ZAD4	–0.26	0.46
Lambda		50.50	20.00
% of Var0		390.3	140.3

The factor structure matrix was obtained with the help of an oblique Oblimin rotation. The first factor was dominated by the projections of the running time (TEK) and the final result (REZUL). The greatest part of competitive successfulness in biathlon could therefore be ascribed to the influence of the successfulness of ski-running. The second factor was dominated by the projections of the shooting times (STR).

Somewhat lower projections were obtained for variables that measure successfulness of shooting from the viewpoint of hits (ZAD). The projection of the variable representing the result of the competition ($r = -0.72$) was also quite high on the second factor, successfulness is therefore divided between both factors. The two

factors could be therefore named FACTOR OF RUNNING SUCCESSFULNESS (1. factor) and FACTOR OF SHOOTING SUCCESSFULNESS (2. factor). The latter is also conditioned by the time the competitors use while shooting and the number of hits.

The correlation between the two obtained factors confirmed the hypothetical general component of successfulness in biathlon (Table 8). The correlation coefficient ($r = -0.32$) was statistically significant ($p < 0.01$).

Table 8. Component Correlation Matrix

	FACTOR 1	FACTOR 2
FACTOR 1	10.00	
FACTOR2	–0.32**	10.00

** $p < 0.01$.

In all probability we could say that the highest level of successfulness in biathlon requires the development of such a general ability that simultaneously regulates and co-ordinates both ski-running as well as shooting abilities.

Success at the World Championship at the 20 km competition was significantly correlated with most of the elementary variables of successfulness (Table 9).

The highest correlation ($r = -0.80$) was found (see Table 9) between the result (REZUL) and successfulness from the viewpoint of the number of hits (ZAD). The number of hits therefore contributed the most to the regression function (beta = –0.63). The net running time (TEK), obtained as the sum of all the five circle times, was highly correlated with the final result (beta = 0.76). The contribution of running (beta = 0.59) was therefore significantly higher than the contribution (beta = 0.11) of the summed shooting time (STR). On the basis of these results we could accept the hypothesis that the most decisive factor in biathlon (20 km distance) are the sum running time (TEK) and the successfulness of shooting — the number of hits (ZAD).

Table 9. Presentation of linear correlation coefficients and regression analysis at the level of elementary and also derived variables of successfulness

	Mult r	r	Beta	Sig t	% of Var0
REZUL	10.00				
TEK	10.00	0.76**	0.59	0.00	0.45
TEK1		0.69**	0.18	0.00	0.15
TEK2		0.71**	0.16	0.00	0.15
TEK3		0.72**	0.26	0.00	0.25
TEK4		0.71**	0.22	0.00	0.20
TEK5		0.71**	0.27	0.00	0.25
STR	10.00	0.46**	0.11	0.00	0.05
STR1		0.47**	0.29	0.00	0.18
STR2		0.39**	0.33	0.00	0.26
STR3		0.37**	0.33	0.00	0.24
STR4		0.17	0.46	0.00	0.32
ZAD	10.00	–0.80**	–0.63	0.00	0.50
ZAD1		–0.33**	0.36	0.00	0.14
ZAD2		–0.41**	0.50	0.00	0.31
ZAD3		–0.46**	0.46	0.00	0.27
ZAD4		–0.51**	0.51	0.00	0.28

* $p < 0.05$ ** $p < 0.01$.

Legend: Mult R — multiple correlation between predictors and criterion variable (REZUL),
r — correlations between predictor variables and the criterion (REZUL),
Beta — standardised coefficients of partial regression,
Sig t — statistical significance of standardised regression coefficients (Beta),
% of Var0 — percentage of partial contribution of each predictor to the explained variance of criterion.

The shooting time is not important from the viewpoint of the end result, however, it is without doubt important for a good execution of the shooting. Therefore the competitor must optimise the shooting time in such a way as to achieve the greatest number of hits. We can substantiate our hypothetical discussion with the percentage of contribution of the individual variables to the final result. The number of hits contributed 50%, net running time 45% and shooting time 5%. The lowest contribution to the competitive result

was from the shooting time (STR). Its contribution is minimal and probably does not represent a great problem from the viewpoint of competitive successfulness. However, by weighting the shooting time, its significance would greatly increase. This would force the competitors to complete their shooting in as short a time as possible, as longer shooting times could not be compensated any more with faster running and good shooting. Biathlon would become even more interesting in such a way and the number of abilities influencing the end result would increase. A simulation of such weighted time has confirmed our hypothesis (see Table 10a).

Table 10a. Results of regression analysis, after the shooting time was quadrupled (STRSIM)

	Mult r	r	Beta	Sig t	% of variance
REZUL	10.00				
STRSIM		0.72**	0.36	0.00	0.24
TEK		0.66**	0.49	0.00	0.36
ZAD		–0.76**	–0.52	0.00	0.40

** $p < 0.01$.

Table 10b. Matrix of inter-correlation coefficients between simulated shooting time (STRSIM) net running time (TEK) and shooting time (STR)

	STRSIM	ZAD	TEK
STRSIM	10.00	–0.31**	0.27**
ZAD	–0.31**	10.00	–0.23*
TEK	27**	–0.23*	10.00

The simulation of a fourfold pondering of shooting time (see Table 10a) increased greatly the correlation with the final result ($r = 0.72$), which also affected the beta coefficient (beta = 0.36) in the regression equation. The amount of explained variance due to this variable increased from 5% to 24% — this is a significant contribution to the complete variance of competitive successfulness.

The value of the correlation coefficient (see Table 10b) between the shooting time (STR) and the number of hits (ZAD) has a nega-

tive sign and is relatively low (r = –0.31). Something similar can be said also for the correlation coefficient between the shooting time (STR) and the running time (r = 0.27).

If the shooting time (STRSIM) were increased, the relative independence between the basic components of successfulness would also increase, that is would be strengthened even further. The essence of biathlon is supposed to be balancing the influence of all three independent components of successfulness to such an extent, as to make each contribute a significant part to the end result. And this is precisely what the weighted shooting time does accomplish.

DISCUSSION

Successfulness in biathlon — the 20 km distance — is according to the competitive rules defined as the sum of three, at first glance, independent components: net running time (TEK), shooting time (STR) and the penalty time caused by missed shots (ZAD). An analysis of the relationship between the individual components of successfulness has shown that the contribution of the number of hits (50%) and the net running time (45%) is of almost equal importance. In addition is can be found that the penalty times for the missed shots are relatively well set by the rules and enable a completely equivalent share both to the number of hits and the time spent at the competition (sum of running time and shooting time) in defining the final result in biathlon.

The recognition that there is a statistically significant correlation (see Table 2), albeit not a high one, between the successfulness in ski-running and the successfulness from the viewpoint of the number of hits, is important for practical work in the training process of competitors in biathlon. This correlation can be ascribed to the great difference in competitive quality of the individuals in our sample. A relatively low correlation coefficient (r = 0.23) favours the hypothesis that ski-running training does not effect significantly the shooting precision and vice-versa, this hypothesis

was also confirmed with factor analysis (see Table 9) where two latent components of competitive successfulness emerged. The two latent factors are statistically significantly correlated. This means that each component of successfulness in biathlon requires relatively separate methods of training, but also that one should develop both at the same time through situational training. The connecting link is the shooting time (STR), of course in connection with the shooting procedure (arrival at the shooting range, assuming the shooting position, calming the weapon with precise aiming at the target and squeezing the trigger). It is precisely this situational training that develops the highest general components of successfulness in biathlon, responsible for regulating and coordinating running and shooting abilities [1]. In such a way an optimal technique of ski-running and shooting can be built and form that kind of "kinetic melody" which enables the competitor to optimally execute his competitive technique. Just high successfulness in running or just in shooting is therefore not enough in biathlon. The greatest art of training hides in an optimal combination and integration of, at first glance, completely independent components of successfulness. It is a fact that only those competitors arrive at the top, which are highly successful both in ski-running by itself and also in shooting — either according to shooting time or precision. However, their greatest advantage is precisely in their ability for an optimal integration of both components of successfulness [5] in competitive conditions of course — often presenting the competitors with maximal stressful efforts and physical pressures.

The net shooting time (STR) contributed only 5% to the final competitive result. In the simulation of a fourfold increase of the shooting time, this share increased to 24%, which represents a significant part of the variance of competitive successfulness. Notwithstanding, shooting time is an important factor of successfulness, which has shortened considerably in the last years [2].

On the basis of the results of this study we could confirm the hypothesis on a statistically significant contribution of the individual components to successfulness in biathlon. The hypothesis on the independence of the individual components of successfulness was also confirmed with factor analysis. It is also evident that the

net running time is an independent factor, but is also statistically significantly correlated with the net shooting time and the precision of shooting (number of hits).

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

PERCEIVED PHYSICAL COMPETENCE AND ACHIEVEMENT GOAL ORIENTATIONS AS RELATED WITH PHYSICAL ACTIVITY OF ADOLESCENTS

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ABSTRACT

Achievement goal orientations and perceived physical competence are two dimensions of motivation that interact to affect exercise behavior. Research to date, however, has primarily dealt with these two variables in isolation. The present study examined the relationships between achievement goal orientations and perceived physical competence with physical activity of adolescents. Two hundred and twenty six 13–14-year-old adolescents completed TEOSQ and C-PSPP to measure orientations toward adopting task and ego goals and perceived physical competence. Physical activity was assessed using 7-day activity recall. Adolescents with high physical activity score showed higher task orientation and ego orientation (males) and higher scores for C-PSPP subdomains. Physical activity correlated significantly positively with task orientation ($r = 0.32 - 0.44$), perceptions of sports competence ($r = 0.22 - 0.33$), physical condition ($r = 0.27 - 0.40$), body attractiveness ($r = 0.22 - 0.26$) and strength ($r = 0.23 - 0.34$). Multiple regression analysis revealed that predictors accounted for 24% of the variation in exercise behavior.

Key words: adolescents, perceived physical competence, goal orientation, exercise

INTRODUCTION

Understanding and enhancing motivation has long been one of the most popular research topics in sport psychology. Recently, theoretical frameworks focusing on self-percepts and their effect on motivated behavior has spawned many approaches to motivation research [5, 23]. Perceived competence has been theorized as having an effect on achievement motivation. Specifically, the motive to participate or continue participation may be mediated by an individual's perception of competence toward a task or activity [35]. The focus of this study is based on a Harter's [19] competence motivation theory and Nicholl's [27] achievement goal theory. These theoretical frameworks are mainly derived from educational domain and have been applied with some success in the sport and physical activity context [14, 24, 37, 41].

Competence motivation theory

Harter's [18, 19] competence motivation theory has had an important impact on research in the physical activity arena. Harter [19] argues that individuals who perceive themselves to have high competence in a particular domain combined with internal control, will be more intrinsically motivated in that domain. These perceptions of competence will encourage effort, persistence, high levels of achievement, and the experience of more positive affect. Several studies in youth sport have supported these theoretical assumptions. Specifically, studies have revealed that children with high perceptions of physical competence possessed higher perceptions of internal control, intrinsic motivational orientations, and levels of participation and performance than their low perceived competence counterparts [14, 28, 38, 39]. Thus, perceived competence becomes a critical variable of interest from both a theoretical and applied perspective when studying children's physical achievement behaviors. According to Harter [18] competence motivation theory, perceived competence is viewed as a domain-specific indicant of self-esteem that is responsive to a number of antecedent variables

and that influences affective and motivational outcomes. Moreover, Harter's model is sensitive to developmental differences, which is critical to the investigation of children's and adolescents experiences in physical activity behavior [39].

Achievement goal theory

Nicholl's [27] goal perspective theory proposes that two goal orientations, task orientation and ego orientation, operate in achievement contexts. Nicholl's theory states that individuals strive to demonstrate competence through task or ego goal orientations. According to the theory, task orientation implies task mastery or personal improvement as reflecting high competence and subjective success. Thus, perception of competence tends to be self-referenced if the individual is task oriented. Ego-oriented individuals, on the other hand, tend to gauge their own competence by comparison to others. In these individuals, high ability and perceived goal accomplishment are predicted on displaying superiority over those to whom they compare themselves [9, 10].

Recent research has indicated that an examination of individual differences in goal perspectives provides insight into behavioral variability and motivational processes in sport [1, 8, 12, 16, 34]. Fox *et al.* [16], for example, in a study of children's generalised reactions in sport, found that children in low task/low ego group had significantly lower scores on perceived sport competence and enjoyment than children with different goal profiles. Recently, Vlachopoulos and Biddle [37], in a study of likely determinants of achivement-related affect in physical education, found a positive association between task orientation and success perception, but not between ego orientation and success perception. However, there is relatively little data indicating the role of both perceived physical competence and achievement goal orientations on physical activity behavior of adolescents [11].

In sum the purpose of this study was to examine the relationships between perceived physical competence and achievement orientations with physical activity in adolescents.

METHODS

Subjects

Two hundred and twenty six volunteer male and female adolescents from urban schools of city Tartu, Estonia took part in the study. Specifically, the sample consisted of males (N = 119, mean age 13.6 yrs) and females (N = 107, mean age 13.9 yrs). The subjects of this study were not regularly participating in organized sport activities and trainig groups.

Measures

Perceived physical competence

The C-PSPP [40] consists of four subdomains that assesses perceptions of sports competence (Sport), physical condition (Condition), body attractiveness (Body), and strength (Strength). Three of the four subdomains (Condition, Body, and Strength) were based on modifications of Fox's original PSPP scales [15]. Harter's [20] sport/athletic competence scale was used for the Sport scale since it was conceptually similar to Fox's [15] original sport scale and had been previously validated with children. A fifth subscale assessing global physical self-worth (PSW) was also included in the profile. Each scale contained six items in a structured alternative format [40].

The subject first determined which of two options was most characteristic of him or her and then decided whether it was *really true* or only *somewhat true* to him or her. This format has been shown to reduce the tendency toward socially desirable responses (21). The values ranged from 1 to 4, with the midpoint of the scale occurring at 2.5.

Achievement goal orientations

Task and Ego Orientation Sport Questionnaire (TEOSQ).

In order to assess adolescent's orientations toward adopting task and ego goals, Task and Ego Orientation in Sport Questionnaire [13] was employed. The questionnaire requested subjects to think of when they felt most successful in sport and then indicate their agreement with 13 items reflecting a task (e.g., "I feel successful in sport when I do my very best") and ego (e.g., "I feel successful in the sport when the others can't do as well as me") orientation to subjective sport success. Responses were recorded on a 5-point Likert-type scale. A mean score was calculated for the task and ego orientation subscales with a low score of 1 and a high score of 5.

Physical activity

The 7-day physical activity recall [30] was used to quantify moderate to vigorous physical activity of the adolescents. The 7-day recall was modified from its original design as an interviewer-administered survey to a self-administered survey. This was done by reproducing the questionnaire verbatim from the cited reference [30] and asking the subjects to read the instructions and to respond in writing. In contrast, the original instructions called for an interviewer to verbally provide the instructions to the subjects and having the interviewer record the verbal response from them. A similar modification of the 7-day recall to a written instrument was employed by Blair *et al.* [3]. In this written form, subjects reported time spent in moderate (3–5 METs), hard (5–7 METs), very hard (7 or more METs) activity intensity categories and sleep (1 MET) over the past seven days. Light activity (1–3 METs), which comprises most of the day, was determined by substraction. In the current study, the two-week test-retest reliability was administered with a random subsample of 36 adolescents and their parents. Their reliability was 73, indicating an acceptable quality of measurement.

Data analysis

Pearson's correlations and multiple regression were used as statistical methods. Independent variables of low and high physical activity groups were compared with univariate ANOVA and post-hoc Sheffe test. Multiple regression analysis was performed with physical activity as dependent variable.

RESULTS

Descriptive statistics for independent variables of low and high activity groups are shown in Table 1. Adolescents with high physical activity levels showed significantly higher ($p < 0.05$) task orientation and ego orientation (in males) and higher scores for C-PSPP subdomains (body attractiveness only in females) when compared to low activity groups.

Table 1. Items means and standard deviations by activity groups

	Total sample (n = 226)		Males (n = 119)		Females (n = 107)	
	HPA	LPA	HPA	LPA	HPA	LPA
Task orientation	3.94±0.37	3.24±0.53*	4.13±0.58	3.19±0.43*	3.68±0.51	3.31±0.63*
Ego orientation	3.43±0.58	3.05±0.65*	3.65±0.72	3.14±0.57*	3.28±0.61	2.85±0.71
C-PSPP subdomains						
Sport	3.22±0.53	2.59±0.59*	3.42±0.65	2.7±0.61*	3.17±0.59	2.33±0.49*
Conditon	3.37±0.58	2.48±0.53*	3.27±0.61	2.62±0.66	3.18±0.53	2.73±0.57*
Body	3.07±0.64	2.79±0.55	3.13±0.54	2.79±0.51	3.06±0.46	2.88±0.52*
Strength	3.15±0.61	2.64±0.62*	3.29±0.49	2.64±0.48*	2.98±0.49	2.76±0.49

* $p < 0.05$ (between activity groups) HPA — high physical activity group LPA — low physical activity group.

Table 2 presents correlation coefficients between physical activity and independent measures. Physical activity was significantly ($p < 0.05 - 0.001$) associated with task and ego orientation (in females) and C-PSPP subdomains.

The summary of multiple regression analysis with physical activity as dependent variable are presented in Table 3. Together, the four predictors accounted for 24% of the variation in exercise behavior. Task orientation was the most influential contributor to the equation (beta = 0.29***).

Table 2. Zero-order correlations between physical activity, achievement goal orientations and C-PSPP subdomains

	Physical activity Total sample	Physical activity Males	Physical activity Females
Task orientation	0.38***	0.44***	0.32***
Ego orientation	0.17	0.11	0.25**
Sport	0.28**	0.33**	0.22*
Condition	0.34***	0.40***	0.27**
Body	0.22*	0.26**	0.16
Strength	0.28**	0.34***	0.23*

* $p < 0.05$, ** $p < 0.01$, * $p < 0.001$.

Table 3. Multiple regression analysis (n = 226)

Predictor variables	Beta	F	R^2 (cum.)
Sport	0.21**	5.24**	0.11
Strength	0.24**	7.11**	0.15
Condition	0.17**	8.54**	0.19
Task orientation	0.29***	10.14***	0.24

** $p < 0.01$, *** $p < 0.001$.

DISCUSSION

This study has shown that perceived physical competence and achievement goal orientations are important factors to consider when investigating the determinants of exercise behavior of adolescents. Specifically, it was found that task ang ego goal orientation and perceived physical competence were related with exercise

behavior of adolescents accounting for 24% of the variance in physical activity.

Much concern has been expressed about the sedentary lifestyles adopted by a considerable number of children and adolescents [31]. Promoting physical activity, therefore, is a major priority in conteporary public health. However, the study of the likely determinants or correlates of physical activity has not been easy and many questions remain unanswered [1]. Dishman and Sallis [7], for example, argued that a primary goal of sport is related with deeper understanding of the process of personal motivation for physical activity. Consequently, there is a need to address the issue of psychological correlates of adolescent's involvement in physical activity. Clearly, a large number of factors have the potential to impact of exercise behavior, and variables identified may affect males and females differently [2].

Children's perceptions of their physical competence have been found to be powerful and consistent predictors of their participation and continuing interest in sport and physical activity [14, 22, 38]. The findings of present study suggest that different components of physical self perception are related with physical activity levels of adolescents. Although the correlation analysis showed only moderately low positive zero-order correlations between exercise behavior and perception of sports competence, physical condition, body atractiveness and strength, these associations were consistent for both sexes. Thus, the results of present study support the Harter's competence motivation theory, which states that individuals who perceive themselves to have high competence in a particular domain, will be more instrinsically motivated in that domain [18]. Accordning to Roberts *et al.* [28], evidence indicates that the correlations of children's perceived physical competence and their actual physical competence increases positively as children get older. Previous studies have shown that children aged 8 and 11 years are not very accurate in perceiving their own physical competence [20, 23, 26, 35]. Rudisill *et al.* [29] examined the relationship between children's (age 9–12) perceived and actual physical competence, They concluded that children of this age are moderately accurate at perceiving their personal motor competence.

However, less research has been done concerning the association between perceived physical competence and the actual level of physical activity of adolescents [16]. Biddle and Armstrong [2], in a study of psychological correlates of physical activity in 11–12 year old children, found that the active girls were characterized more by higher scores on perceptions of attractive body, as well as physical self-worth and global self-esteem.

Recent motivational research has indicated that an examination of individual differences in goal orientation provides insight into behavioral variability and motivational processes in sport and exercise behavior [8, 10, 34]. Summarizing previous studies on this topic, Duda [11] argued that young people would exhibit increments in performance, feel competent in sport and physical education, and be more active when a task orientation prevails. The results of current study also revealed that adolescents with higher levels of physical activity were more task oriented when compared to low activity counterparts. In addition, active adolescents showed also higher ego orientation. These trends were, interestingly, appearent in both males and females. Therefore, for active adolescents, both personal improvement as well as normative perception of competence when compared to others, were important predictors of exercise participation. Given these results and the previous studies on the motivation-related correlates of goals, it would not be surprising that research to date has revealed a positive correlation between achievement goal orientation and adolescent's level of physical activity [6, 11].

The present study leaves several theoretical and empirical issues unresloved. Like in most previous adolescents research, it uses cross-sectional data and does not provide definite causal evidence. In additon, the study explains only modest amount (24%) of the variation in physical activity, suggesting the need for more refined multiple psychological as well as socio-cultural variables. It may be that relatively low explained variance in present study underscores the fact that physical activity is complex, i.e. involves different sports and forms of exercise and is performed within different contexts such as organized clubs, informal groups and on individual basis. There are indicators that different contexts of sport

and exercise and even specific sports and forms of exercise are in part predicted by different psychological and behavioral variables [4, 17, 32, 33, 36].

In summary, task orientation and perceived physical competence was associated with physical activity in adolescents. Adolescents with higher task orientation and perceived physical competence showed significantly higher levels of activity involvement compared with less active counterparts.

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Acta Kinesiologiae Universitatis Tartuensis, vol. 4, 1999

PREDICTION OF 2000 METRE ROWING ERGOMETER PERFORMANCE FROM METABOLIC AND ANTHROPOMETRIC VARIABLES IN MALE ROWERS

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ABSTRACT

In ten male experienced rowers (18.9 ± 1.7 yrs; 186.2 ± 6.3 cm; 79.3 ± 7.3 kg; %body fat: 10.5 ± 2.3%), the relationships between metabolic parameters, anthropometric characteristics and 2000 metre rowing ergometer performance were analysed to test the hypothesis that a combination of these variables would predict performance better than any of these categories of variables alone or any single variable. The rowers were subjected to three measurement session on a rowing ergometer (Concept II, Morrisville, USA). An incremental exercise test to determine maximal oxygen consumption ($\dot{V}O_{2max}$), the corresponding maximal aerobic power (Pa_{max}) and anaerobic threshold (AT_4), a 2000 metre time trial and a 40 seconds "all-out" test to determine maximal anaerobic power (P40) were performed. Height, body mass, body mass index, lean body mass, cross-sectional area of thigh, muscle mass, skeletal mass, $\dot{V}O_{2max}$, Pa_{max}, AT_4, $\dot{V}O_2$ at AT_4, rowing economy (i.e., LA_{350W}) and P40 were the major predictors of rowing ergometer performance. Multiple regression analysis demonstrated that the prediction models using the combination of categories of anthropometric and metabolic variables predicted 2000 metre rowing ergometer performance times best ($R^2 = 0.99$), followed by the equa-

tions using only metabolic (R^2 = 0.98) and anthropometric (R^2 = 0.86) parameters, respectively. It was concluded that 2000 metre rowing ergometer performance is dependent on both anthropometric and metabolic physiological categories.

Key words: rowing ergometry, anthropometry, metabolic adaptation

INTRODUCTION

A typical rowing competition takes place on a 2000 metre course and lasts 6–7 minutes. A rower has to develop more than 200 times a stroke with a peak force of 800 to more than 1000 Newton [19]. Rowing demands a high level of strength and endurance [6]. A large body mass is involved in rowing, and body size and body mass are undoubtedly performance related factors [6, 17,19].

In rowing, maximal oxygen consumption ($\dot{V}O_{2max}$) is known to be a good predictor of competition success [12, 15, 16, 19]. Research has shown that $\dot{V}O_{2max}$ and anaerobic threshold (AT) are both well correlated with rowing performance [17, 19]. Aerobic metabolism has been reported to supply 70–86% of the competition energy expenditure with the remaining energy being supplied by anaerobic sources [15]. The elevated blood lactate (LA) concentrations (15–17 $mmol \cdot l^{-1}$) measured at the end of rowing competition [17] suggest that the energy contribution from the anaerobic energy system would influence 2000 metre rowing performance.

Performance prediction models have successfully been developed for running [13], cycling [2] and ergometer rowing for elite schoolboys [15] using anthropometric and metabolic variables. In the experiment reported here, a multiple regression analysis was performed to develop prediction equations from metabolic and anthropometric variables alone, as well as in combination to predict the performance of 2000 metre rowing ergometer test for male rowers. It was hypothesized that a combination of metabolic and

anthropometric variables would predict the performance of 2000 metre rowing ergometer test better than any of these categories of variables alone or any single variable.

METHODS

Subjects

Ten male experienced rowers volunteered to participate in this study. The subjects were training regularly and had being do so for the last 4.70 ± 1.83 years. Measurements took place at the end of competition season (i.e., in September). The rowers were familiarised with the laboratory procedures and possible risks before providing their consent to participate in the experiment as approved by the Medical Ethics Committee of University of Tartu. Each rower was tested on three separate occasions over a two week period with at least three days between tests. The rowers were asked not to participate in any physical activity in the 24 hours before testing and to abstain from eating for 3 hours before testing.

Anthropometrics

The height (Martin metal anthropometer) and body weight (medical balance scale) of subjects were measured and body mass index (BMI, $kg \cdot m^{-2}$) calculated. Sum of six skinfold thicknesses (i.e., triceps, subscapular, abdominal, supraspinale, front-thigh, medial calf) was measured (Holtain skinfold caliper, UK) [3]. Body density was determined according to the skinfold prediction equation of Durnin and Womersley [4] and percent body fat was calculated from body density according to the equation of Siri [18]. In addition, muscle mass was calculated according to Martin *et al.* [10]. While skeletal mass was calculated according to Martin [11]. Cross-sectional area (CSA) of thigh was estimated according to Hawes [7].

Testing procedures

All exercise tests were performed on a wind resistance braked rowing ergometer (Concept II, Morrisville, USA). The rowers were fully familiarised with the use of this apparatus. Power and stroke frequency were delivered continuously by the computer display of the rowing ergometer. Heart rate (HR) was measured continuously and stored at five seconds intervals during all exercise tests (Sport-tester Polar Vantage NV, Kempele, Finland).

At the first measurement session, a progressive incremental exercise test to maximal intensity was performed [12, 20]. This was carried out for the determinations of $\dot{V}O_{2max}$ (in $l \cdot min^{-1}$ and $ml \cdot min^{-1} kg^{-1}$), maximal aerobic power defined as the mechanical power where $\dot{V}O_{2max}$ is reached (Pa_{max} in W) and the power corresponding to the 4 $mmol \cdot l^{-1}$ blood LA concentration (AT_4 in W) for each subject. The test started at 150 W and power output was increased every three minutes by 50 W until individual maximum. Stroke rate during the test varied between 18 and 34 $strokes \cdot min^{-1}$. Capillary blood samples for enzymatic determination of LA (Lange, Germany) [5] were taken from a fingertip during a 30 second rest interval at the end of each intensity [12, 20]. Expired gas was sampled continuously for the measurement of $\dot{V}O_2$ (TrueMax 2400 Metabolic Measurement System, Parvo Medics, USA). The analysers were calibrated prior to the test using commercial gases of known concentration. To establish that $\dot{V}O_{2max}$ was reached, the following criteria were used: attainment of a plateau in $\dot{V}O_2$ with increasing work rate, or when this plateau was not observed, a respiratory exchange ratio exceeding 1.1, an end exercise LA concentration higher than 9 $mmol \cdot l^{-1}$, and a theoretical maximal HR [12]. The AT_4 was assessed by linear interpolation from the LA versus work rate curves. The LA concentration in blood at 350W was used as a parameter of "rowing economy".

At the second measurement session, the subjects were asked to cover a 2000 metre distance on a rowing ergometer in the least time possible (2000 metre "all-out" test). The measurement session started with a 10 minutes warm-up exercise at 40–45% $\dot{V}O_{2max}$. Capillary blood samples for enzymatic LA analysis were taken

from fingertips three and five minutes after the exercise (Lange, Germany) [7].

Third measurement session consisted of a 40 seconds "all-out" test on a rowing ergometer. The session started with a 10 minutes warm-up exercise at 40–45% $\dot{V}O_{2max}$. After two minutes rest, a 40 seconds "all-out" test on a rowing ergometer was performed and the mean work rate (P40 in W) of this test recorded [19]. Capillary blood samples for enzymatic LA analysis were taken from fingertip three and five minutes after the exercise (Lange, Germany) [5].

Statistical methods

Descriptive statistics (mean ± standard deviation [SD]) for each of the dependent variables were determined. Differences were estimated with independent t-tests with an error of estimate set to 0.05. Pearson Product Moment Correlation coefficients were used to determine the strength and relationship between each of the dependent variables and competition time on a rowing ergometer. Again, an alpha level of 0.05 was used. Forward stepwise multiple regression analysis was used to predict the 2000 metre competition result on a rowing ergometer as independent variable and different rowing ergometer test results and anthropometric parameters as dependent variables.

RESULTS

Mean (±SD) metabolic characteristics and anthropometric parameters of subjects on a rowing ergometer and their interrelationships with the results of 2000 metre rowing ergometer performance are presented in Table 1. AT_4 (W) corresponded to 74.22 ± 4.24% of Pa_{max} (W) work rate. There was a large spread in the individual anthropometric characteristics and rowing performances as indicated by the large SDs. Significant relationships were observed between the results of 2000 metre time trial on a rowing ergometer and the following parameters: height, body mass, BMI, LBM, CSA

of thigh, muscle mass, skeletal mass, $\dot{V}O_{2max}$, Pamax, AT_4, $\dot{V}O_2$ at AT_4, LA_{350W} and P40.

Table 1. Anthropometric and metabolic characteristics of rowers (X ± SD), and correlations with 2000 metre rowing ergometer time

Variable	X ± SD	Range	Correlation with 2000 metre time
Age (yrs)	18.90 ± 1.66	18.00–21.00	–
Height (cm)	186.20 ± 6.25	179.00–198.00	–0.77*
Body mass (kg)	79.27 ± 7.30	69.40 – 94.80	–0.91*
BMI ($kg \cdot m^{-2}$)	22.83 ± 1.10	21.35 – 24.69	–0.63*
Sum 6 SF (mm)	44.70 ± 9.53	30.00 – 62.00	0.02
% body fat	9.34 ± 1.44	7.50 – 11.90	0.01
LBM (kg)	71.78 ± 5.85	63.80 – 83.50	–0.91*
Thigh CSA (cm^2)	258.01 ± 27.89	210.60 – 307.11	–0.66*
Muscle mass (kg)	49.50 ± 6.06	41.03 – 62.17	–0.85*
Skeletal mass (kg)	10.98 ± 1.48	9.28 – 13.84	–0.88*
$\dot{V}O_{2max}$ ($l \cdot min^{-1}$)	4.854 ± 0.631	3.910 – 6.130	–0.76*
$\dot{V}O_{2max}kg^{-1}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	61.61 ± 5.59	54.90 – 71.30	–0.13
Pa_{max} (W)	369.07 ± 37.37	330.90 – 449.20	–0.97*
AT_4 (W)	274.80 ± 40.67	230.00 – 350.00	–0.96*
AT_4 ($l \cdot min^{-1}$)	4.132 ± 0.633	3.140 – 5.160	–0.87*
LA_{350W} ($mmol \cdot l^{-1}$)	11.82 ± 4.82	4.05 – 17.30	0.96*
P40(W)	613.87 ± 81.88	519.60 – 783.30	–0.76*
2000 m (min)	6.64 ± 0.30	6.05 – 6.93	–

BMI, body mass index; Sum 6 SF, sum of triceps, subscapular, biceps, suprailiac, supraspinale and mid-thigh skinfolds; LBM, lean body mass; CSA, cross-sectional area; $\dot{V}O_{2max}$, maximal oxygen uptake; Pa_{max}, maximal aerobic power; AT_4, anaerobic threshold; LA_{350W}, lactate at the power of 350W; P40, power of 40 seconds "all-out" test; 2000 m, 2000 metre "all-out" test.

* Statistically significant, $p < 0.05$.

Multiple regression equations in Table 2 demonstrate that the prediction model using anthropometric and metabolic variables predicts performance time of 2000 metre rowing ergometer trial best ($R^2 = 0.99$), followed by the equations comprising only metabolic ($R^2 = 0.98$) and anthropometric ($R^2 = 0.86$) variables alone.

Table 2. Multiple regression equations, adjusted R^2 and standard error of the estimate (SEE) for the individual physiological categories and the overall best predictor multiple regression equations

Physiological category (variables in equations)	Multiple regression equation	R^2 SEE
Combination of categories		
Pa_{max} (W)	Time (sec) = 193.229 – 0.038 × Pa_{max} (W) +	0.99
LA_{350W} (mmol·l^{-1})	3.248 x LA_{350W} (mmol·l^{-1}) + 0.075 ×	2.24 sec
CSA thigh (cm^2)	CSA thigh (cm^2) + 1.331 × Height (cm) –	
Height (cm)	0.066 × P40 (W) – 0.931 × Muscle mass (kg)	
P40 (W)		
Muscle mass (kg)		
Metabolic		
Pa_{max} (W)	Time (sec) = 427.610 – 0.363 × Pa_{max} (W) +	0.98
LA_{350W} (mmol·l^{-1})	3.011 × LA_{350W} (mmol·l^{-1}) + 0.251 ×	3.31 sec
AT_4 (W)	AT_4 (W)	
Anthropometric		
LBM (kg)	Time (sec) = 623.959 – 2.233 ×	0.86
BMI (kg·m^{-2})	LBM (kg) – 2.934 × BMI (kg·m^{-2})	7.55 sec

DISCUSSION

Scientists have developed performance prediction models for different sports [2, 13]. Recently, Russell *et al.* [15] developed a performance prediction model for junior sweep rowers on a rowing ergometer. The use of laboratory-based rowing ergometer tests and prediction models allows coaches and scientists to predict on-water rowing performance and to identify potentially talented rowers [15]. This is in accordance with Lamb [9] and Rodriguez *et al.* [14] studies who have observed that rowing ergometry replicates the kinematic movement pattern and simulates the metabolic demands of on-water rowing. Therefore, rowing ergometers are commonly used to measure individual physiological performance variables and training changes [12, 15, 16, 19, 20].

Multiple regression equations in Table 2 demonstrate that the prediction models using the combination of categories of anthropometric and metabolic variables predicted performance times best on a rowing ergometer, followed by the equations using only metabolic parameters. This is in contrast to the results of Russell *et al.* [15] study, who found that anthropometric variables alone predicted the performance time best on a rowing ergometer. This demonstrates that the results of our study and the study of Russell *et al.* [15] must be viewed with the caution. The prediction equations were developed specifically for male scullers in our study. While the subjects were junior sweep rowers in Russell *et al.* [15] study. These differences could be explained by the fact that sweep rowers have been reported to be taller and heavier, and are also characterised by a greater muscle development as compared to the sculling subjects [1].

Height, body mass, BMI, LBM, CSA of thigh, muscle mass, skeletal mass, $\dot{V}O_{2max}$, Pa_{max}, AT_4, $\dot{V}O_2$ at AT_4, rowing economy (i.e., LA_{350W}) and P40 were the major predictors of rowing ergometer performance (see Table 1). This is in consistent with the anthropometric data of adult male rowers that have been published emphasizing the importance of body mass and body size for rowing performance [1]. As demonstrated in many studies, a typical rower is tall, heavy and lean athlete with a high amount of slow-twitch muscle fibres in working muscles [6, 8, 19]. A large muscle mass is achieved by the long hours of aerobic training combained with weight training [15, 19]. This type of training also results in a rower with a large aerobic capacity and metabolic efficiency [15, 19] as demonstrated by the high values of $\dot{V}O_{2max}$ and AT_4 indices of our subjects (see Table 1).

In summary, the development of performance prediction models based on laboratory data has practical importance for talent identification and for the development and assessment of training programmes. The results of present study suggest that rowing ergometer performance is better assessed using a combination of specific anthropometric and metabolic variables.

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