

## Biomechanical, Neuro-muscular and Methodical Aspects of Running Speed Development

by

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*The purpose of present review article is to gather the most important findings in the field of speed development including biomechanical, motor and neuro-muscular factors. Maximum speed is a complex motor ability, which manifests itself in real sports situations and is an important factor in various sports disciplines. Efficiency of maximum running is defined with frequency and the length of stride. Both variables are mutually dependant; they also depend on the processes of central regulation of motor stereotype. From the biomechanical point of view, a running stride as a basic structural unit depends on eccentric-concentric muscular cycle of take-off action. Utilisation of elastic strength in muscular-tendon complex and pre-activation of the gastrocnemius muscle is highly important in this element. Maximum running is very limited hereditary motor ability with characteristic of reduced possibility for controlling movement. Cerebellum, co-activation of muscles in kinetic chain and the frequency of activation of motor units play important roles in controlling the activation of agonists and antagonists. The prime goal of training is to create an optimal model of motor stereotype in the zone of maximum speed. Such process has to be long term and methodical.*

**Key words:** sprint, motor stereotype, take-off action, speed barrier, stride frequency, stride length, speed of reaction

### Introduction

All movements at work, in sport activities and everyday life demand a high degree of efficiency. These processes strive towards strong synchronisation, automation and high level of rationalisation. People execute movements according to specific biomechanical conditions and on a basis of interaction between the managing system (central neural system) and the managed system (locomotive apparatus). Interaction between these two systems is a result of motor control, which main task is providing coordination and optimisation of movement, efficiency of movement and motor learning.

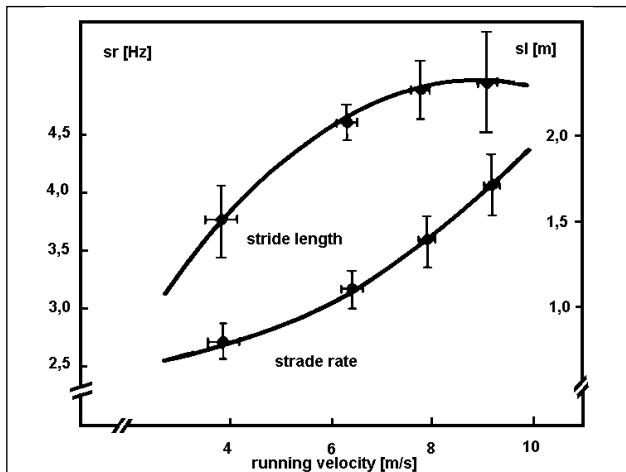
Maximum speed, which is produced during movement, depends on various factors. These factors are related to morphological and physiological characteristics, energetic mechanisms, age, gender, motor abilities, inter- and intra-muscular coordination and optimal biomechanical technique of movement. Locomotive speed in the form of sprinting is one of the most important abilities, which defines the successfulness of athletes in many sport disciplines. From the genetic (hereditary) motor programme aspect, speed can be classified into primary phylogenetic human movements. In specific sports situations, speed is being manifested in a form of the »three-segment model«. The model consists of speed, strength and coordination. Pondering of individual

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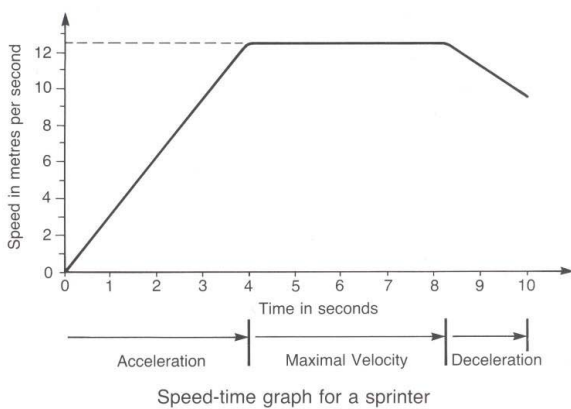
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segments of this model depends on the particularities of specific sport disciplines.



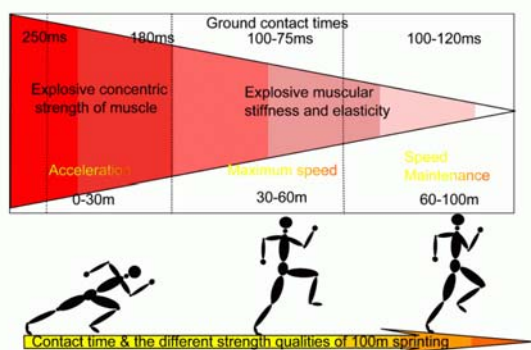
**Figure 1**

*Relationship between speed, frequency and length of stride*



**Figure 2**

*Dynamics of sprinters speed*



**Figure 2**

*Differentiation of strength typology in sprinting runs*

## **Biomechanical aspects of speed**

Maximum running speed is a product of the frequency and the length of stride. Both variables are mutually dependant; they are also linked to the processes of central regulation of movement, to the morphological characteristics, motor abilities and energetic processes. The relationship between the frequency and the length of a stride is individually defined and automated. Changing one variable results in changes of the second. When a length of a stride is increased, the frequency decreases and vice versa. With increased speed both variables increase (Figure 1).

Frequency of stride depends on:

- Functioning of central-neural system
- Inter- and intra-muscular coordination
- Central and peripheral neural fatigue

The length of stride depends on:

- Morphological characteristics (length of lower extremities)
- The reactive force of surface (impulse at take-off)
- Duration (time) of contact phase
- Dynamic flexibility in hips
- Take-off distance
- Touchdown distance

Development of maximal running speed follows certain rules, which are based on the level of motor abilities, morphological characteristics and the degree of biomechanical efficiency and rationalisation of movement. In the development of locomotive speed there are three basic phases: phase of acceleration, phase of maximal speed and phase of deceleration. Variables that to the greatest extent generate the change of speed are length and frequency of stride. In the first phase an athlete develops 80-90% of his maximal speed. Sprinters generally achieve their maximal speed. After 80-90 metres speed begins to decrease (Figure 2).

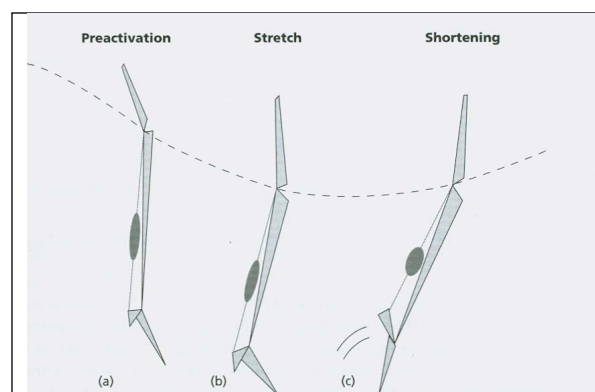
During the acceleration phase both: frequency and length of stride increase. The duration of contact in sprinters stride is shortening and the time of flight increases. With a shorter duration of the contact phase the type of strength changes as well. During the acceleration, the duration of contact phase is relatively long; the most important motor ability is power-strength of concentric modality. In the subsequent phases of sprinting the duration of contact is shorter and the importance of elastic energy increases significantly (Figure 3).

In the phase of maximum speed both frequency and the length of stride are relatively constant, the proportion between the contact and flight phases of sprinters stride is also stabilised. The zone, where sprinters achieve their absolute maximum speed is very limited. In principle, the best sprinters can sustain this phase for 10 to 20 metres. The zone of maximal speed is located somewhere between 60 and 80 metres in men and between 50 and 70 metres in elite women. Maximal speed is always a product of optimal stride length and the frequency of stride. Donatti (1996) and Mackala (2007) state that there are no differences in the length of stride between elite and sub-elite sprinters, with differences existing only in the frequency of stride. Therefore, frequency of stride is one of the most important variables of maximal speed (Mero, Komi, Gregor 1992, Delecluse et al. 1995, Donatti 1996). In the last phase of sprinting run, between the 80 and 100 metres, velocity begins to decrease on a scale of 0.5 to 1.5 metres per second. Deceleration is caused by central and peripheral fatigue. Central fatigue is manifested as an error in the muscle activation, meaning that the number of active motor units and the frequency of neuro-muscular impulses decrease. This results in a lower degree of inter- and intra-muscular coordination, which is eventually being manifested with the decrease in frequency of steps, particularly in the last 10 metres of 100-m sprint. Central fatigue is correlated to the smaller activity of cortical and sub-cortical centres (Semmler, Enoka 2000). Increased fatigue at the end of the 100-m sprint is also caused by peripheral nerves and metabolic processes in the muscles. In the last 10-metres the duration of contact and the length of stride increase. The control of movement is during this phase of speed at the lowest level. This mostly depends on the quality of sprinters technique, as the disruption of these parameters is smaller in best sprinters than in the runners of medium quality.

### *Neuro – muscular aspects of speed*

Take-off action in sprinting stride is a key generator for development of maximal speed. Movement of sprinters is evaluated according to their horizontal velocity. The largest inhibitor in this movement is gravitational force; therefore, sprinters need to primarily develop sufficiently large vertical reactive force on the surface in the take-off action, which in itself consists of three phases. The first phase is placing a foot on the surface, followed by

the amortisation phase and extension phase. Take-off action of stride in sprinters is the best example of eccentric-concentric muscular cycle (stretch-shortening cycle). In eccentric phase a certain amount of elastic energy is being accumulated in the muscular-tendon complex, which can then be utilised in the second phase. When looking at the production of reactive force onto a surface, muscles in the eccentric phase need to develop as large force as possible in as short time as possible. Transition time needs to be as short as possible and has an important effect on the efficiency of eccentric-concentric contraction. Tendons and ligaments, which resist the extension, can store up to 100 % more elastic energy than muscles (Luhtanen, Komi 1980, Mero, Komi, Gregor 1992). Pre-activation of the gastrocnemius (calf muscle) is extremely important for the mechanics of take-off; this muscle is being activated 80 milliseconds prior to foot touching the surface (Figure 4a). Pre-activation creates a stiffness of plantar flexors (muscles) in the moment when the front part of the foot touches the surface. Increased stiffness of the muscles together with the minimal amplitude of movement in an ankle joint enables better transfer of elastic energy from eccentric to concentric contraction (Mero et al. 1986, Kyrolainen et al. 2001). When loaded during the sprint, tendons elongate up to 3-4% of their length, any elongation above this limit represents a potential danger for rupture. Tendons and ligaments act as springs, which store elastic energy. Excessive elongation of tendons results in transformation of elastic energy into heat, namely into chemical energy. High temperature of cells – fibroblasts and collagen molecules, which are the building material for tendons, could facilitate the possibility for injuries of this part of locomotive apparatus (Huiling 1999).



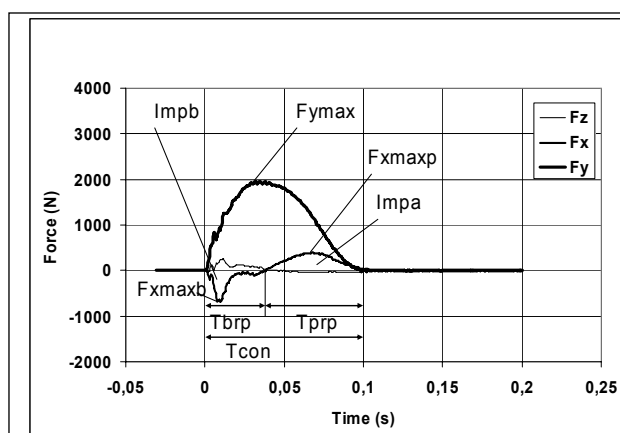
**Figure 4**  
*Eccentric – concentric muscular contraction in the stride of sprinters (Komi, 2000)*

In the second phase an extension of muscular – tendon complex takes place (Figure 4b), whereas previously stored elastic energy is being utilised in a form of efficient propulsion of sprinters stride. The main absorber in this phase is the quadriceps (thigh muscle). Increased co-activation of agonists and antagonists (m. vastus laterali, m. biceps femoris, m. gastrocnemius and m. tibialis) increases the stiffness of knee- and ankle joints. In this way, the entire leg is being prepared for contacting the surface. Increased stiffness of the ankle joint in the sprint reduces the consumption of chemical energy in the following muscles: m. gastrocnemius – m. lateralis – m. medialis and m. soleus (Kuitunen, Komi, Kyrolainen 2002). Muscular activation of plantar flexors and the knee extensors increases in the pre-activation phase in proportion with the increase of speed. In addition, pre-activation of m. triceps surae together with the stretching reflex facilitates high degree of stiffness of muscles in the extension phase of the take-off.

Extension of muscular and tendon complex is managed and coordinated with two motor reflexes: monosynaptic stretch reflex and the polysynaptic reflex of Golgi tendon organ. These two reflex systems form a recurring coupling for maintaining the near optimal muscle length (reaction to stretching) and the reaction to excessive elongation of tendons. Receptors of stretch reflex – muscle spindles are placed parallel to muscle fibres. When muscle is being extended as a result of external force acting on it, muscle spindles also extend. As a result of muscle spindle extension, alpha motor neurons are being activated, which in turn activate reflex contraction of elongated muscles as a reaction to stretching. Golgi tendon organs are placed serially with muscle fibres. These receptors react exclusively to the forces, which are being developed in the muscles and do not react to any changes in length. If muscle effort increases rapidly, Golgi tendon complex prevents muscular contraction. Subsequent decrease of muscular effort prevents injuries to muscles and tendons (Jacobs, Ingen Schenau 1992, Zatsiorsky, Kraemer 2006). In the phase when foot is placed on the surface and in the amortisation phase, extensors are being elongated and they produce contraction in the same muscle on the basis of the stretch reflex. At the same time the effort of large muscles activates Golgi tendon organ, which prevents activity of the muscle. As a result of specific training, activation of Golgi tendon organ is being inhibited and thus athletes can withstand large forces at landing without decreasing

produced force of the muscles. As reversible contraction of muscles represents an integral part in many sports movements, it needs to be specially trained and taught. Jump training with reversible contraction has nowadays become an integral part of speed training in sportsmen. These so-called plyometric jumps and plyometric training produce high quality results in the development of take-off strength. In order for such training to be successful, a long term all-around preparation with different means and methods of strength training is required. On the other hand, plyometric jumps can cause serious injuries by athletes.

The time from a foot being placed on a surface until the end of take-off in the stride of sprinters lasts between 80 – 100 milliseconds. The cumulative contact time is shorter in elite sprinters. The shorter the time of contact, the better the frequency and the higher force take off on a surface. The relationship between the contact phase and the flight phase in sprinters stride is 20: 80. The largest reactive force of the surface is noticed 30 to 40 milliseconds after the first contact with the surface (Mann, Sprague 1980). According to Mer, Komi, Gregor (1992), the vertical reactive force of the surface in sprinters reaches 200 to 300% of their body weight. The largest reactive force of the surface is in sprinters developed in the middle phase of the contact – the phase of maximal amortisation (Figure 5). In order to develop maximal locomotive speed, the largest possible force needs to be developed in the shortest possible time. Mastering the optimal mechanics (technique) of sprinting run is a condition for the utilisation of the force, which is being generated by the neuro-muscular system.



**Figure 5**  
Force-time curves during the contact phase  
(Čoh, Dolenc 2002)

### *Intra- and inter-muscular coordination of speed development*

In order to understand the dynamics and the changes of stride frequency and length in the training of maximal speed, the function of central neural system needs to be explained. Muscle force is not only defined by the amount of included muscle mass, but also by the degree of participation of individual muscle fibres. In order to manifest muscle force, muscles need to be activated in a certain way. Coordinated movement of several muscle groups depends on inter-muscular coordination. Basic characteristic of elite sprinters is efficient coordination of activated fibres in individual muscles and muscle groups. These sprinters have better inter- and intra-muscular coordination. Neural system generates muscle force in three ways: with activation and deactivation of individual motor units, with a frequency of releasing of motor units and with synchronisation of motor units. All three ways are based on the motor units, which represent basic elements in the working of neuro-muscular system. Every motor unit consists of a motor-neuron, which is located in the spinal cord, and from the muscle fibres, which are innervated. From the contraction point of view, motor units can be divided into slow and fast twitch. Slow motor units are specialised for extended use at a relatively low speed. They consist of small motor-neurons with a low threshold of release and they are adapted to aerobic activities. Fast muscular or motor units are specialised for relatively short lasting activities, which require strength, speed and a high degree of force development. They consist of large motor-neurons with a high threshold of release, axons with high speed of implementation and muscle fibres, which are adapted to powerful anaerobic activities. Motor units follow the "all or nothing" law, meaning that any motor unit in any time is either active or inactive. The fastest speed of shortening of fast muscle fibres is four times faster than in slow muscle fibres (Zatsiorsky, Kraemer 2006). Human muscles in general consist of motor units with slow or fast action. Sprinters and athletes, who are required to develop large speed or force in a unit of time, have predominantly motor units with fast actions.

In volitional contractions, the activation of muscle fibres depends on the size of motor-neurons with a "size principle" being applied. First, small motor-neurons with a low threshold of excitation are being activated. With increasing demands for development

of large force, larger motor-neurons with the fastest contraction twitch and highest threshold of excitation are being recruited as last. Mixed muscle types consist of motor units with slow and fast activation regardless of the degree of muscular effort and the speed being manifested. Only highly trained athletes manage to activate motor units with fast activation.

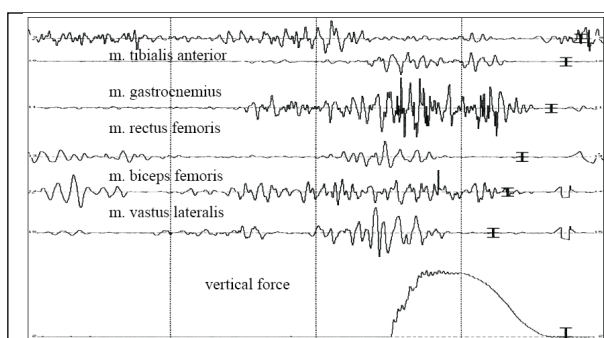
Training of maximal locomotive speed is related to high coordination of movement. In a cycle of sprinters stride, there are more than 60 lower-leg muscles active, which have to work in a synchronised and coordinated way. In execution of precise movements, motor units usually do not work at the same time. In order to produce maximal force, which is one of the key factors of maximal speed, the largest amount of slow and fast motor units needs to be recruited as well as the maximal frequency of release and simultaneous work of motor units in a period of maximal voluntary effort. The prime goal in speed training is a creation of optimal movement model, which is based on the coordination of different muscle groups.

### *Controlling maximal speed*

Speed is a motor ability with a strong genetic endowment related to the central-neural system. Shortage of neuro-muscular coordination is one of the limiting factors of speed as the possibility for optimal control of movement decreases with the increase in speed of movement. The larger the speed, the higher is deviation from the ideal movement model. Control of movement is at its lowest level under conditions of maximal speed. Maximal speed belongs to the category of so-called terminal movements, which have precisely set structure with a defined beginning and end of movement (Latash 1994). Terminal movements differ according to their dynamic and kinematics volumes. Every terminal movement requires its adequate motor program. Motor program is defined as a group of simultaneous and successive commands to muscles in order to start and later end a desired movement. On the level of central neural system and spinal cord, motor programme is represented with a group of efferent signals, which travel down the motor nerves to muscles. It is known that the large number of various fast movements is controlled as the "open loop" process with centrally stored programme and without any feedback information (Schmidt 1990). The most important functions in these movements are cerebellum and spinal cord. High speed of movement does not

allow any analyses or correction. Precise movement control lies therefore in the work of cerebellum and relies on the information, which arrives there mostly via proprio-receptors that are located in joints and connective tissues of muscles. Spinal reflexes of muscular-tendon source in the area of spinal cord also play an important part in movement control. Any change in the length and tension of muscles is being transferred via stretch reflex path. Stretch reflex serves as a servo-mechanism, which enforces excitation effect on alpha motor neurons, thus increasing the precision of control of muscle group work. One of the most important problems in motor control is the role of agonist and antagonist muscles and their direct effect on kinematics and dynamics of movement through appropriate type, intensity and time sequence of muscle force effect. In fast terminal movements, such as sprinting, development of force is a key factor of movement efficiency. Variables of motor programme are force of agonist muscles, maximal force of antagonist muscles, time delay of antagonist muscles, time of achieving the maximal force of antagonist muscles, co-activated relationship of muscles in the function of their place in kinetic chain, length of a movement, terminal position, starting position, time length of a movement and the speed of a movement (Ilic 1999).

Development of maximal running speed requires very subtle inter-muscular coordination of muscle groups of lower extremities. The most important are the following muscles: m. gluteus maximus, m. tibialis anterior, m. soleus, m. gastrocnemius, m. rectus femoris, m. biceps femoris, m. vastus lateralis (Figure 6). Identifying strategic muscles, which generate the take-off force, is very important from the sports training point of view in order to optimise technique



**Figure 7**  
EMG activation of muscles of lower extremities in the phase of maximal speed (Čoh, Dolenc 2002)

and prevent injuries. In the take-off phase muscles develop the reaction force with a magnitude of 280 to 350 kp in a time interval of 85 – 95 milliseconds (Čoh, Dolenc 2002). Some studies from the field of electromyography and isokinetics of sprinters stride have revealed that biceps femoris (hamstring muscle) is one of the most important muscles in developing maximal speed (Semmler, Enoka 2000, Čoh, Dolenc 2002). This muscle often gets injured during sprinting, therefore its prevention with adequate training is very important. Training of maximal speed is from the aspect of physical preparation of athletes related to running technique, which is particularly difficult to control in the conditions of maximal speed. Optimal neuro-muscular coordination is the main limiting factor of maximal speed. Therefore, the forming of correct dynamic stereotype is a long term process, which has to have precisely defined technique and has to begin at an early age of the athletes.

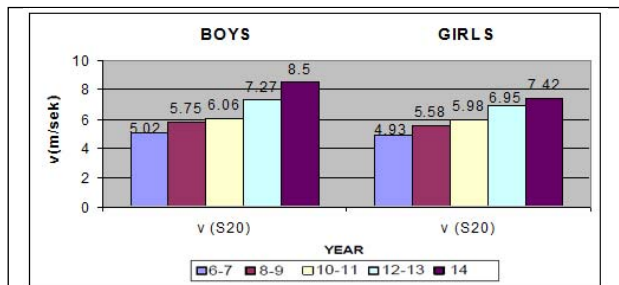
### Methodology of speed development

In methodology of training for development of maximal speed there are two paths available: the synthetic and analytic. Approach synthetic training the emphasis is on the development of speed as a whole, whereas in analytic training the emphasis is on separate training of individual speed components. In both paths the basic requirements are that movement is being executed of maximal speed, with optimal rational technique where fatigue does not prevent realisation of maximal speed of movement. One of the basic training methods for development of speed is the method of repetitive. Basic aim is to overcome own maximal speed (Zatsiorsky 1975). Speed has to be maximal or sub-maximal, as only such training pushes the limit of speed in desired direction. Rest period is determined by two processes: central fatigue – excitation of neural system and physiological – biochemical variables. Following fast movements, the excitation of neural system drastically increases and rapidly decreases after loading. Considering this factor, the rest period could be relatively short. However, the length of rest period also depends on anaerobic functions. Rest period in speed development training needs to be sufficiently short that the level of excitation is not reduced to minimum and sufficiently long that the functional variables return to their initial or near initial values.

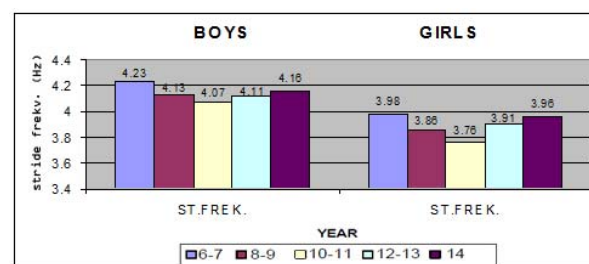
Running is an elementary inborn movement with already built program in the central neural system. Efficiency of running from the speed point of view is relatively individual, which depends on a variety of hereditary functions. In the development of children, a term “natural – biological development of sprinters speed” is used (Figure 7). This development depends on body height, body weight, development of motor abilities and the formation of motor stereotypes of movement.

Development of maximal speed is not constant, but has certain oscillations, particularly in the adolescence period, when morphological and motor characteristics of youth change. Due to acceleration of longitudinal parameters, frequency and length of stride change (Figures 8 and 9). The length of stride increases and the frequency of stride decreases significantly. Frequency does not change only as a result of morphological changes, but also due to disruption of proprio-receptive mechanisms for movement control. The biggest differences in the development of maximal speed of pupils of both genders occur between the ages of 12 and 14, mainly in boys due to development of strength. The duration of contact phase of sprinters stride in boys is rapidly reduced after the age of 12 (Figure 10). Duration of contact phase is one of the main criteria in selecting young sprinters (Mero, Luhtanen, Komi 1986, Mero, Komi, Gregor 1992). Synthetic principle of speed development suggests large amount of spontaneous training of children and youth in different sports, where the ability is manifested also with other motor characteristics. Development of speed has to be related to complex motor situations with a strong informational movement component. Namely, this is a period of so-called “sensitive phase” in the development of children (9-13 years), which is very suitable for development of speed potential. Central neural system is being developed, particularly emphasised is formation of myelin nerve sheath, which serves as a transporter of neural impulses from central neural system to active muscles. In this period, particularly the speed of transfer of such impulses, which generate the speed of movement, can be influenced.

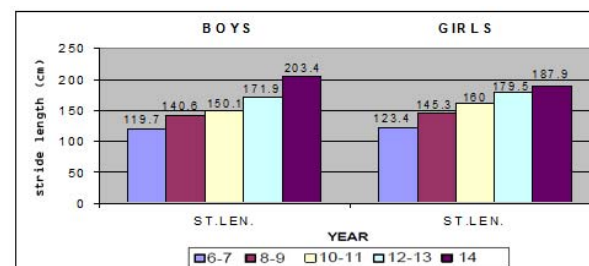
The analytical approach is related to training of individual technical elements of sprint, which are similar in structure to locomotion in sprint. They include ABC exercise of sprinting: skipping, jumping, running with accentuated take-off, jogging etc. These exercises might seem abstract to children,



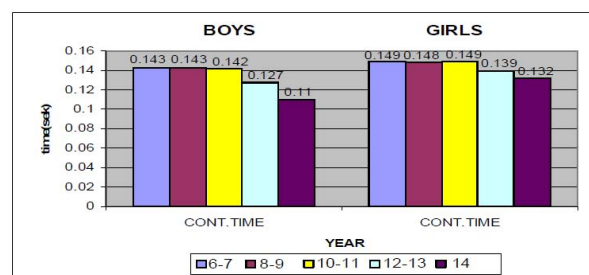
**Figure 7**  
Biological development of maximal speed of boys and girls in primary school (Bračić, Tomažin, Čoh 2009)



**Figure 8**  
Development of frequency of stride in boys and girls in primary school (Bračić, Tomažin, Čoh 2009)



**Figure 9**  
Development of stride length in boys and girls in primary school (Bračić, Tomažin, Čoh 2009)



**Figure 10**  
Duration of contact phases of sprinters stride for boys and girls in primary school (Bračić, Tomažin, Čoh 2009)

however, their role in creation of correct technical running model and prevention of technical errors is very important.

Running is a natural genetic need of children. Maximal locomotive speed is an ability, which in children and youth has to be trained with small volume due to two reasons:

1. Children and youth have yet not developed mechanisms of movement control under maximal loading. Consequences are unnatural movement, jerking movements and movement with number of errors.
2. There is a possibility for "speed barrier" occurring, which could result in stagnation of development or even in deterioration of the ability. Generally speaking, inadequate training (narrow specialisation) can lead to formation of certain stereotype in central regulation of movement, which would prevent development of speed. Speed is being based on a specific motor programme. The sooner maximal speed is developed, more programs become stabilised

and lead to prevention of progress in this motor ability.

Numerous repetitions, which are necessary for creation of automated and rational movement, lead to creation of motor stereotype and consequently to stabilisation of movement. Together with stabilisation some kinematics – dynamic variables set; they are manifested with the length and frequency of stride. So-called "speed barrier" occurs, which was first explained by Soviet researcher Ozolin in 1970. The main contradiction in the development of maximal speed is following: in order to increase speed, numerous repetitions of specific move are required; on the other hand larger number of repetitions leads to strong dynamic-kinematics stereotype and strong speed barrier. In addition, the increase of training volume does not have positive effects, but even more stabilises the achieved speed of movement. Stabilisation of movement is the main inhibitor of development of speed potential.

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