The sprint start: Biomechanical analysis of kinematic, dynammic and electromyographic parameters

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ABSTRACT

The start and transition to the acceleration phase of a sprint race is a very complex movement sequence, requiring high muscle activation and effective integration of acyclic and cyclic movements. The purpose of this study was to understand the mechanisms of the start and facilitate the development of appropriate training methods for one athlete, a female hurdler with a best time of 13.19. The aim was to measure the major kinematic and dynamic parameters as well as the EMG activation of muscles in the start. The focus was on 1) the block velocity in a dependent relationship with the development of force in the rear and front blocks, 2) the block acceleration in the first two steps and 3) the EMG activity of seven key muscles. The results of the study include data on 15 start-related parameters and analysis of the EMG activity in both legs during the start.

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Introduction

An efficient start is crucial for a competitive performance in sprint races. Studies conducted to date, most of which were partial biomechanical studies, have identified the following parameters for a good start: reaction time; optimal position of the starting blocks in relation to the starting line; height of the sprinter's centre of mass (CM) in the set position and the block velocity, which is mainly a result of the force impulse on both the rear and front starting blocks (MERO, LUHTANEN, & KOMI, 1983; COPPENOLLE & DELECLUSE, 1989; KORCHEMNY, 1992; McCLEMENTS, SANDERS & GANDER, 1996; HARLAND & STEELE, 1997; MERO et al., 2006). These parameters are interdependent and each is conditional on the central movement regulation processes, biomotor abilities, energetic processes and morphological characteristics of the athlete (MANN & SPRAGUE, 1980; BUHRLE et al., 1983; MORAVEC et al, 1988; MERO, KOMI & GREGOR, 1992; LOCATELLI & ARSAC, 1995).

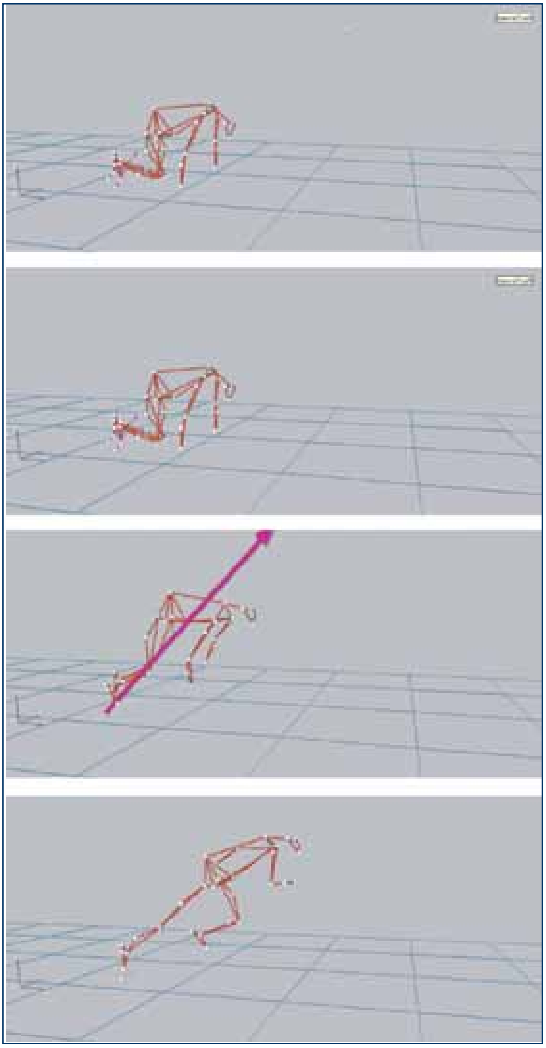


Figure 1

The start directly influences the first phase of the block acceleration. The performance of this sequence is a specific motor challenge requiring the athlete to rapidly make and integrate an acyclic movement followed by a cyclic movement. The accuracy of an analysis of such a complex motor activity largely depends on proper measurement procedures and the technologies available for the work.

The aim of this study was to measure the major kinematic and dynamic parameters of the start and analyse the electromyographic (EMG) activation of the muscles in the start of a single athlete. Our focus was on 1) the block velocity in a dependent relationship with the development of force in the rear and front blocks, 2) the block acceleration in the first two steps and 3) the EMG activation of the following muscles: *erector spinae*, *gluteus maximus*, *rectus femoris*, *vastus medialis*, *vastus lateralis*, *biceps femoris* and *gastrocnemius medialis*. With the information gained, it should be easier to understand the mechanisms of the start and to develop appropriate training methods.

Methods

Subjects

The study sample was one female athlete whose specialty is the 100m hurdles (age: 23, height: 1.67m, weight: 56.1kg, personal best: 13.19).

Experimental procedure

The athlete executed eight starts from which the data was processed and analysed. The starts were performed with the starting blocks set in the medium position. The distance between the blocks and the horizontal distance between the front block and the starting line are given in Table 1. This position provided optimal conditions for the development of the force impulse on the rear and front blocks as well as the rapid clearing of the blocks (MERO & KOMI, 1990). Recordings of the starts for 3-D kinematic analysis were made with a system consisting of nine CCD video cameras (Smart – 600, BTS Bioengineering) with a frequency of 60Hz. Data on the kinematic parameters were processed by the BTS Smart Analyser programme (see Figure 1). The dynamic model was defined using a system of 17 infra-red sensitive markers. The dynamic parameters of the start were established by means of two independent tensiometric platforms – force plate (Type 9286A, Kistler) on which standard starting blocks were installed. The development of forces in the ver-

Table 1: Block set-up

PARAMETER	Unit	N	Result
Horizontal distance from the front block to the starting line	m	8	0.65 ± 0.04
Horizontal distance between the blocks	m	8	0.29 ± 0.02

Table 2: Results

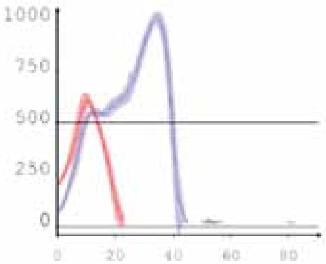
PARAMETER	Unit	N	Result
Reaction time – pre-motor time	ms	8	126 ± 13
Reaction time – rear blocks	ms	8	186 ± 12
Reaction time – front blocks	ms	8	365 ± 21
Total reaction time	ms	8	491 ± 24
Block velocity	m/s^{-1}	8	2.84 ± 0.21
Running velocity – first step	m/s^{-1}	8	4.02 ± 0.24
Running velocity – second step	m/s^{-1}	8	4.78 ± 0.27
Flight phase after blocks	ms	8	82 ± 10
First contact after blocks	ms	8	168 ± 17
Second flight phase after blocks	ms	8	101 ± 20
Second contact after blocks	ms	8	139 ± 22
Maximal force of rear blocks	N	8	628 ± 34
Maximal force of front blocks	N	8	1023 ± 30
Force impulse of rear blocks	Ns	8	72 ± 4
Force impulse of front blocks	Ns	8	138 ± 6
Total force impulse	Ns	8	210 ± 11

tical (Fy), horizontal (Fx) and latero-medial (Fz) directions was registered at the front and rear blocks (see Figure 2). A 16-channel electromyograph (BTS Pocket EMG, Myolab) was used to analyse EMG activity. Superficial EMG muscle activity was detected by means of bipolar surface electrodes Ag-AgCl, which were fastened to the specific locations of muscle motor units, following thorough skin preparation (see Figure 3).

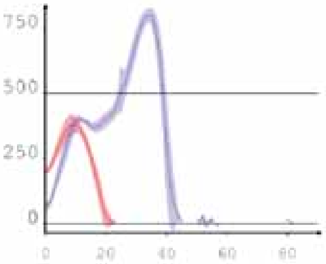
Results

Kinematic and dynamic characteristics of the sprint start

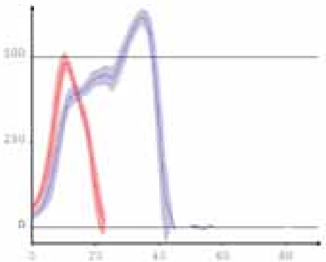
The reaction time, i.e. pre-motor time, is defined by the time interval from the gun signal to the EMG activation of muscles. The athlete's reaction time was 126 ± 13ms (Table 2).



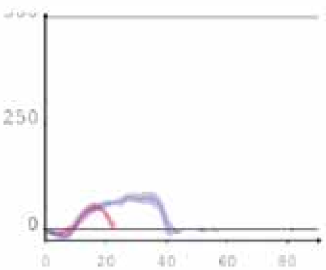
Absolute Force	Right double	Left double	Left single
Peak value (N)	628 ± 34	593 ± 25	1023 ± 30
max.Force ascent (N/msec)	8 ± 2	8 ± 2	7 ± 1
Force Impuls (Nmsec)	72 ± 4	72 ± 7	138 ± 6



Vertical force component	Right double	Left double	Left single
Peak value (N)	386 ± 30	410 ± 10	810 ± 23
max.Force ascent (N/msec)	4 ± 1	6 ± 1	6 ± 1
Force Impuls (Nmsec)	48 ± 3	54 ± 5	105 ± 4



Anterior-posterior force component	Right double	Left double	Left single
Peak value (N)	498 ± 25	438 ± 19	623 ± 22
max.Force ascent (N/msec)	10 ± 1	7 ± 2	4 ± 1
Force Impuls (Nmsec)	50 ± 4	47 ± 4	88 ± 6



Latero-medial force component	Right double	Left double	Left single
Peak value (N)	54 ± 9	61 ± 6	83 ± 11
max.Force ascent (N/msec)	1 ± 0	2 ± 0	1 ± 0
Force Impuls (Nmsec)	3 ± 1	3 ± 1	11 ± 2

Figure 2: Force development on the front and rear blocks.

Figure 3: Placement of surface electrodes for measuring EMG activity

The total reaction time is defined by the pre-motor reaction time and the time of clearing the rear and front blocks (total reaction time = pre-motor time + motor time: reaction time rear block – reaction time front block). The athlete's total reaction time was 491 ± 24ms. The respective times of elite male sprinters range between 310 and 370ms, while those of elite female sprinters are between 350 and 430ms (HARLAND & STEELE, 1997).

The quality of the start depends not only on the reaction time but also on the production of force in the rear and front blocks. Our study subject's maximal force on the rear starting block was 628 ± 34N and on the front starting block was 1023 ± 30N. The rear leg thus produced only 57.9% of the maximal force in the pushing phase of the start. Impulses, i.e. impelling force (impulse = F x t), which is determined as the integral of the area under the force-time curve (Figure 2), is one of the most significant criteria of an efficient start (GUTIERREZ-DAVILA, DAPENA & CAMPOS, 2006). Our athlete developed a force impulse of 72 ± 4Ns on the rear starting block and 138 ± 6Ns on the front starting block. In view of the total impulse (210 ± 11 Ns) the force production/time ratio in the rear and front blocks was 34%:66%. Thus, it may be established that in this case the contribution of the rear foot to the production of force was too small.

Block velocity is defined as the sprinter's velocity at the moment contact with the front starting block is broken. Our subject's block velocity was 2.84 ± 0.21m/s^{-1}. Block velocity is a product of an optimal set position, efficient force production in the pushing phase and a high degree of automatisation of the starting technique. In elite male sprinters it ranges between 3.45 and 3.94 m/s^{-1}, whereas in elite female sprinters it is between 2.80 and 3.35 m/s^{-1} (COPPENOLLE & DELECLUSE, 1989; MERO & KOMI, 1990; McCLEMENTS, SANDERS, & GANDER, 1996; HARLAND & STEELE, 1997).

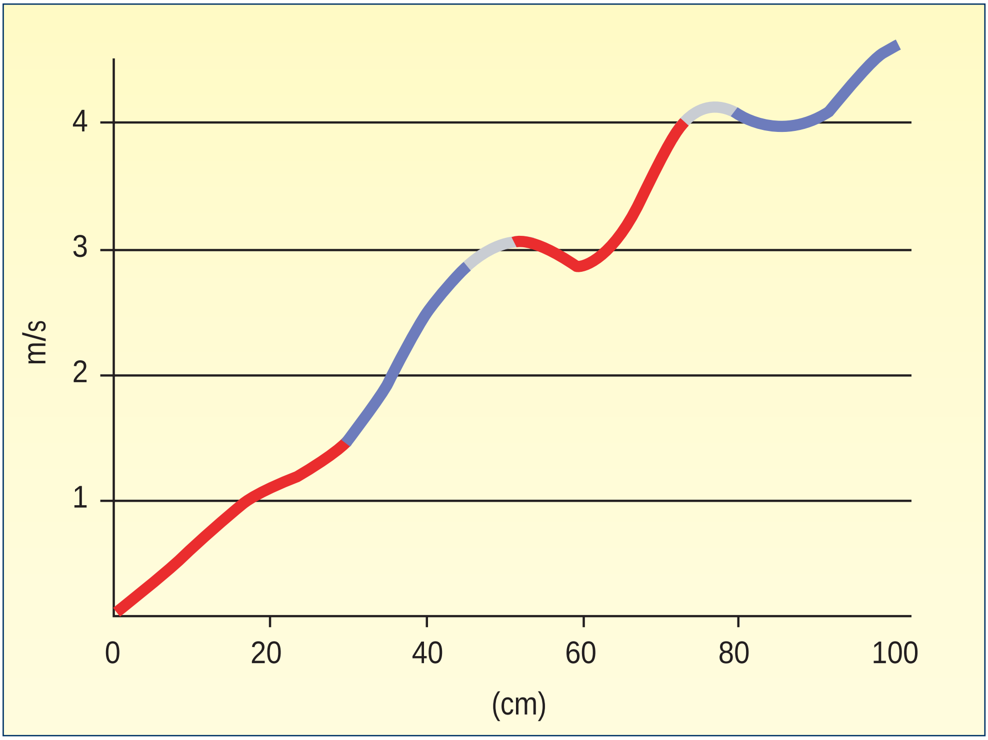


Figure 4: Velocity increase in the first two steps

The quality of the transition from the start to block acceleration is manifested in an increase in velocity in the first two steps. At the end of the first step, the velocity of the body's CM was 4.03 ± 0.24m/s^{-1} and at the end of the second step it was 4.78 ± 0.27m/s^{-1}. In the first two steps, the velocity increased by 1.94m/s^{-1}. When the first two steps were executed, the projection point of the athlete's CM was located in front of the foot's contact with the ground.

The contact phase of a step is divided into the braking phase and the propulsion phase. In the former, the horizontal ground reaction force is negative while in the latter it is positive. Consequently, during the execution of an individual step the velocity fluctuates considerably (Figure 4). In the braking phase of our athlete's first and second steps, the reduction in velocity was 6% to 9%. The contact phase of the first step lasted for 168 ± 17ms, while that of the second step was shorter by 29ms. The flight phase after the push from the first starting block lasted for 82 ± 10ms, while the flight phase between the first and second steps was substantially longer, namely 101 ± 20ms. These results show the great biomechanical changes in the structure of the first two steps, where the contact/flight phase ratio changes, and highlight the importance of the transition from the acyclic movement (start) to the cyclic movement (acceleration) as one of the key mechanisms of sprinting.

Electromyographic characteristics

The results of the study clearly reveal the importance of the force produced in the starting blocks. In the set position, our athlete produced force on the rear block for 186 ± 12ms and on the front block for 365 ± 21ms. Electromyography enables the identification of the participating muscles and the sequence in which they generate force. Muscle force production in a start depends on many factors. The main ones are the maximal number of motor units recruited during contraction, motor neuron excitability and the type of motor units recruited (SALE et al., 1983). The performance of a start involves concentric, eccentric and isometric muscle action. The stimulus is the sound signal. The movement involves the participation of one-joint and two-joint muscles. The situation with two-joint muscles (the biceps femoris and rectus femoris) is particularly complex as the change in the length of the muscle is difficult to define. In the first phase, the *gastrocnemius* is activated with a distinct eccentric contraction, whereas in the second phase it is with a concentric contraction. The *vastus medialis*, *vastus lateralis* and *gluteus maximus* muscles work concentrically. After the gun signal, every leg extensor muscle must contribute maximally to the production of force during the block acceleration, which is consequently manifested in the block velocity. Therefore, the sooner the electrical activity begins in each muscle, the faster the neuromuscular performance is maximised.

Electromyographic activity of the muscles of the rear and front legs

One of the most important extensor muscles is the *erector spinae* (ES), the key role of which in the starting phase is to lift the trunk. Based on the results (Figure 5) it may be established that the greatest activation of this muscle (left–right) is in the phase of clearing the starting blocks. The second activation peak of the ES (left) was recorded in the braking phase of the first step and the third activation peak (right) was in the braking phase of the second step. The average degree of activation of the ES during the start and the start acceleration in the first two steps was higher in the left ES.

The one-joint *gluteus maximus* muscle (GM) showed the highest EMG activation values at the beginning of producing force in the start blocks (Figure 5). The degree of activation was slightly higher in the front (left) leg. The GM of the front leg reached a second activation peak at the end of the push from the starting block. The GMs of both legs showed a constantly high activation during the entire contact phase of the first and second steps. Activation of the GM is minimal in the first and second flight phases.

The double-joint *rectus femoris* muscle (RF) showed relatively low activation at the beginning of the starting action. This was particularly true of the RF of the right leg. The EMG activation of the RF of the right and left legs peaked in the last third of the starting action. The second peak activation of the RF was recorded towards the end of the propulsion phase of the first and second steps. Throughout the cycle (start – first step – second step), the RF of the left leg was slightly more active than the RF of the right leg.

The EMG activation of the one-joint *vastus medialis* muscle (VM) and *vastus lateralis* muscle (VL) of the right leg is seen only at the beginning of the pushing action from the rear starting block. The VM and the VL of the left leg were active throughout the starting phase. A slightly higher degree of activation throughout the starting phase (365ms) was seen in the VL. In this muscle, different degrees of activation were recorded during repeated starts. The VM of the rear leg showed the maximal degree of activation when it touched the ground in the first step after the push from the rear block. Pre-activation of this muscle started already during the first flight phase, which lasted for 82 ± 10ms. Pre-activation of the VM plays an extremely important role in ensuring the rigidity of those muscles that enable the transfer of elastic energy from the eccentric to the concentric contraction. The VM showed a second activation peak in the propulsion phase of the first step. In the braking phase of the first step (eccentric phase), the VM was more active whereas in the propulsion phase (concentric phase), the VL is substantially more active. The execution of the second step is related to the slightly lower activation of the VM and the VL in the braking and propulsion phases.

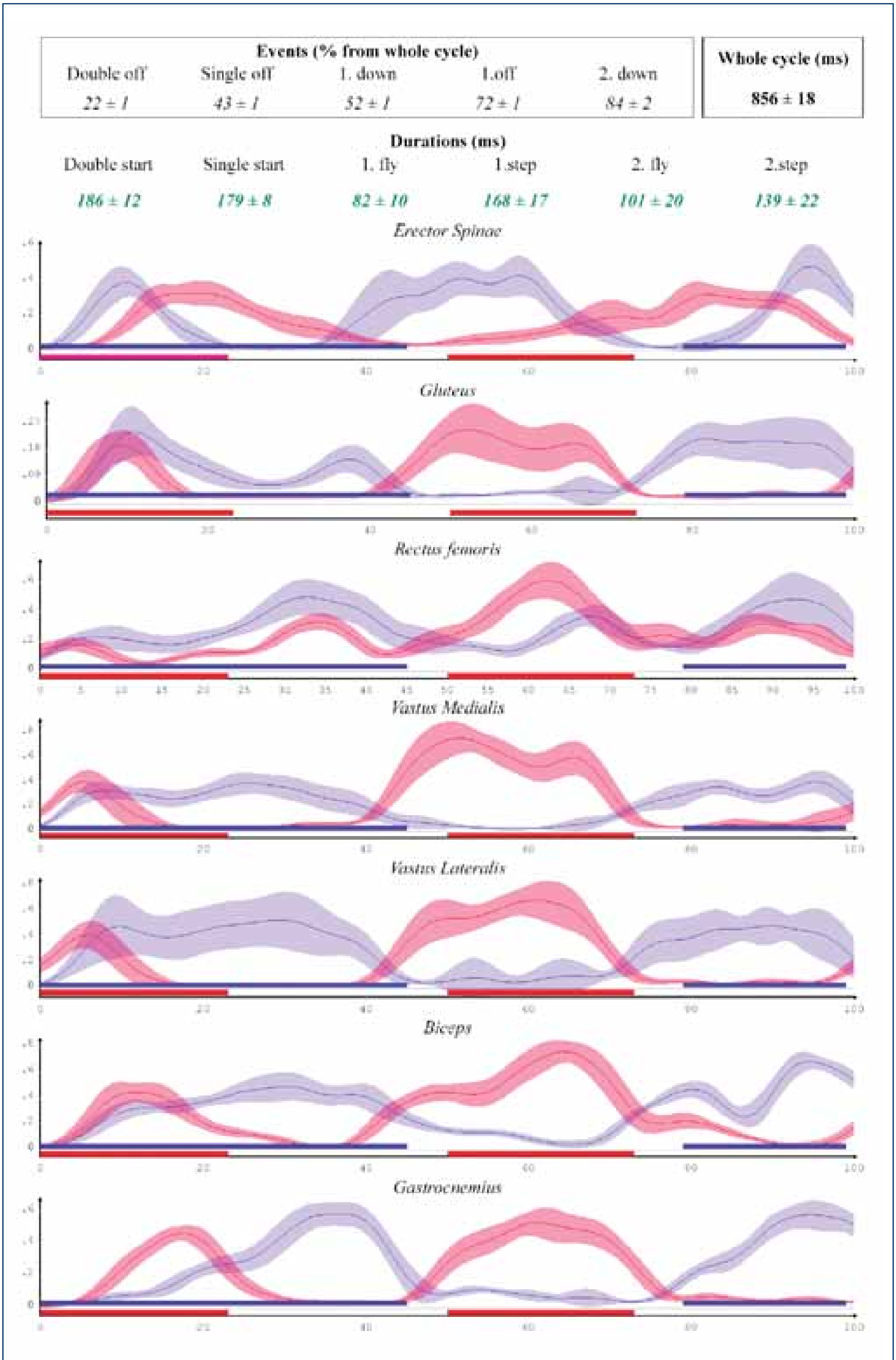


Figure 5: Electromyographic activity of the muscles in the start cycle

The activation modality of the functioning of the two-joint *biceps femoris* muscle (BF) of the right leg is reflected in maximal EMG activity in the first half of the push from the rear starting block. The activation was of a short duration and is related to the time of producing force in the rear block, which lasts for only 186 ± 12ms. The activation of the BF of the front leg was at its peak in the second third of this period and lasted until the last contact of the foot with the front starting block. The peak activation of the BF of the right leg was in the propulsion phase of the first step. This muscle's function is to actively position the foot on the ground and thus decrease the negative ground reaction force. From a biomechanical point of view, execution of the first step is a very demanding task for a sprinter and makes a decisive impact on the efficient transition from start to block acceleration (MERO, KOMI, & GREGOR, 1992; KORCHEMNY, 1992). At the end of the first step, our athlete developed a velocity 1.8 m/s^{-1} higher than that recorded during the push from the front starting block. The activation of the BF of the left foot in the second step is similar and reached its peak in the second third of the contact phase.

In view of the EMG analysis results, the *gastrocnemius medialis* muscle (GA) is one of the most important muscles generating the start and block acceleration. The activity of the GA of the rear leg begins slightly later than the other muscles studied. This depends, in particular, on the position of the foot of the rear leg in the starting block. If the tip of the athlete's foot barely touches the ground, pre-activation does not occur and, consequently, the muscle activation is delayed (MERO & KOMI, 1990). The peak activation of the GA of the rear and front legs can be identified in the final phase of the push off from the blocks. The peak activation was in the GA of the front leg and it directly influenced the block velocity. The substantially lower activation of the GA of the rear leg is manifested in a relatively low force impulse on the rear starting block, accounting for only 52% of the force impulse of the front leg. It may be concluded that our athlete's ability to develop force on the rear block is poor or her movement stereotype start technique is inadequate. Biomechanical studies (MERO & KOMI, 1990; GUISSARD, DUCHATEAU & HAINAUT, 1992; HARLAND & STEELE, 1997) show that the GA is one of the key extensors of the feet and thus a generator of force production on the starting blocks. The block velocity can also be influenced by changing the angle of the foot support of the front starting block. By decreasing the foot support angles the position of the ankle joint changes, the foot dorsiflexion increases and the muscles of the calf extend, resulting in reflex activity and higher block velocity (GUISSARD, DUCHATEAU & HAINAUT, 1992).

Conclusion

The start and transition to the acceleration phase is a very complex sequence, requiring high muscle activation. The EMG activity of the *gastrocnemius* of the right leg is present throughout the contact phase of the first step, which lasts for 168 ± 17ms. Maximal EMG activation is recorded at the point of transition from the braking phase to the propulsion phase of the first step. The execution of the first step is related to a strong force impulse and a high position of the foot, a consequence of a greater inclination of the trunk in the direction of the race. Adequate pre-activation of muscles is important for the efficient execution of the contact phase as it ensures that the muscles are properly rigid to overcome the ground reaction forces. The higher rigidity of the muscles results in better use of the elastic force stored in the serial elastic elements of the muscle. It is the sprinter's task to execute the contact phase of the first step within the shortest time possible. Insufficient rigidity of the muscles, especially of the *gastrocnemius medialis*, *gastrocnemius lateralis* and *soleus*, results in a lowering of the heel, thereby prolonging the contact time and decreasing the block velocity. The execution of the second step is similar from the point of view of the EMG activation of the *gastrocnemius* of the left leg. The time of the contact phase is 17% shorter than that of the first step. The degree of activation starts rising even before the foot touches the ground. It peaks in the middle of the contact phase. The maximal degree of activation of the *gastrocnemius* of the left leg is slightly higher than that of the right leg. Throughout the time cycle, which lasts for 856 ± 18ms and includes the start and execution of two steps, a generally high degree of muscle activation of the *gastrocnemius* of the left and the right legs can be established in all three phases of the motor task, which is important for the production of force in the start and in the block acceleration.

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