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## *Biomechanics of Sprint Running: A Review*

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## Biomechanics of Sprint Running

### A Review

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### Summary

Understanding of biomechanical factors in sprint running is useful because of their critical value to performance. Some variables measured in distance running are also important in sprint running. Significant factors include: reaction time, technique, electromyographic (EMG) activity, force production, neural factors and muscle structure. Although various methodologies have been used, results are clear and conclusions can be made.

The reaction time of good athletes is short, but it does not correlate with performance levels. Sprint technique has been well analysed during acceleration, constant velocity and deceleration of the velocity curve. At the beginning of the sprint run, it is important to produce great force/power and generate high velocity in the block and acceleration phases. During the constant-speed phase, the events immediately before and during the braking phase are important in increasing explosive force/power and efficiency of movement in the propulsion phase. There are no research results available regarding force production in the sprint-deceleration phase. The EMG activity pattern of the main sprint muscles is described in the literature, but there is a need for research with highly skilled sprinters to better understand the simultaneous operation of many muscles. Skeletal muscle fibre characteristics are related to the selection of talent and the training-induced effects in sprint running.

Efficient sprint running requires an optimal combination between the examined biomechanical variables and external factors such as footwear, ground and air resistance. Further research work is needed especially in the area of nervous system, muscles and force and power production during sprint running. Combining these with the measurements of sprinting economy and efficiency more knowledge can be achieved in the near future.

Rapid movement of the body from one place to another is required in many sport activities and especially in sprint running. Several aspects of running have been studied since the beginning of the 1920s (see Amar 1920), when the first kinematic studies of running were reported. Biomechanical variables influencing sprint running include reaction time, technique, electromyographic (EMG) activity, force production, neural factors and muscle structure. Running performance is also influenced by factors external to the runner, such as shoes and the running surface.

Early studies on the velocity-time curve in sprint running were conducted by Hill (1927). Since then there has been a great deal of research, including the mathematical representation of the velocity-time curve of sprint running (for example, Morton 1985). In theory, but also in practical applications, the velocity-time curve is divided into 3 phases: acceleration, constant velocity and deceleration (e.g. Volkov & Lapin 1979). All phases of sprinting have been analysed at recent major athletic competitions (e.g. Moravec et al. 1988). Although many reviews of running biomechanics (e.g. Atwater 1973; Dillman 1975; Williams 1985) have been published, information on sprint running is limited (see e.g. Wood 1987). The present review makes an attempt to complement these reviews with a special effort to summarise the major biomechanical variables affecting sprint running in all phases of the velocity curve.

### ***1. Reaction Time***

Reaction time has been defined as the time that elapses between the sound of the starter's gun and the moment the athlete is able to exert a certain pressure against the starting blocks. Reaction time measurement currently includes the time that it takes for the sound of the gun to reach the athlete, the time it takes for the athlete to react to the sound and the mechanical delay of measurements inherent in the starting blocks. An attempt has been made to separate premotor time and motor time components in the sprint start (Mero & Komi 1990). The former is defined as the time from the

gun signal until the onset of EMG activity in skeletal muscle. Motor time is the delay between the onset of electrical activity and force production by the muscle.

Mero and Komi (1990) used a force threshold of 10% from the maximal horizontal force as the origin of force production as a measure of reaction time. Total reaction time was on average 120 msec, which is smaller than that measured at major championships (Moravec et al. 1988). 120 msec was the minimal reaction time for a valid start in the Rome World Championships in 1987. In fact, no definitive study exists which could be used to establish a minimum reaction time to define a false start. For comparisons of reaction times to be used uniform conditions for measurement must be established. This is not the case at present at major championships, concerning for example the force threshold in the starting blocks (see Moravec et al. 1988).

EMG results (Mero & Komi 1990) showed that total reaction time can be divided into premotor and motor time. However, electrical activity in some muscles started to increase after total reaction time as a result of the multijoint character of the sprint start movement. It is clear that after the gun signal, leg extensor muscles must contribute maximally to the production of force and ultimately to the running velocity. The faster the electrical activity begins in every muscle the faster one can maximise the neuromuscular performance. For improving the starting action, it is desirable that all extensor muscles are activated before any force can be detected against the blocks.

Conclusions regarding reaction times during the start (Dostal 1981; Mero & Artman 1984; Moravec et al. 1988) are: (a) in all sprint events, the reaction times of the best athletes are shorter than 200 msec; (b) in identical events, the average reaction times of women are longer than those of men; (c) reaction times grow in proportion to the length of the race distance; and (d) reaction time does not correlate with the performance levels. This last conclusion means that other parameters (e.g. acceleration, maximum speed) may be more important than reaction time to final race performance.

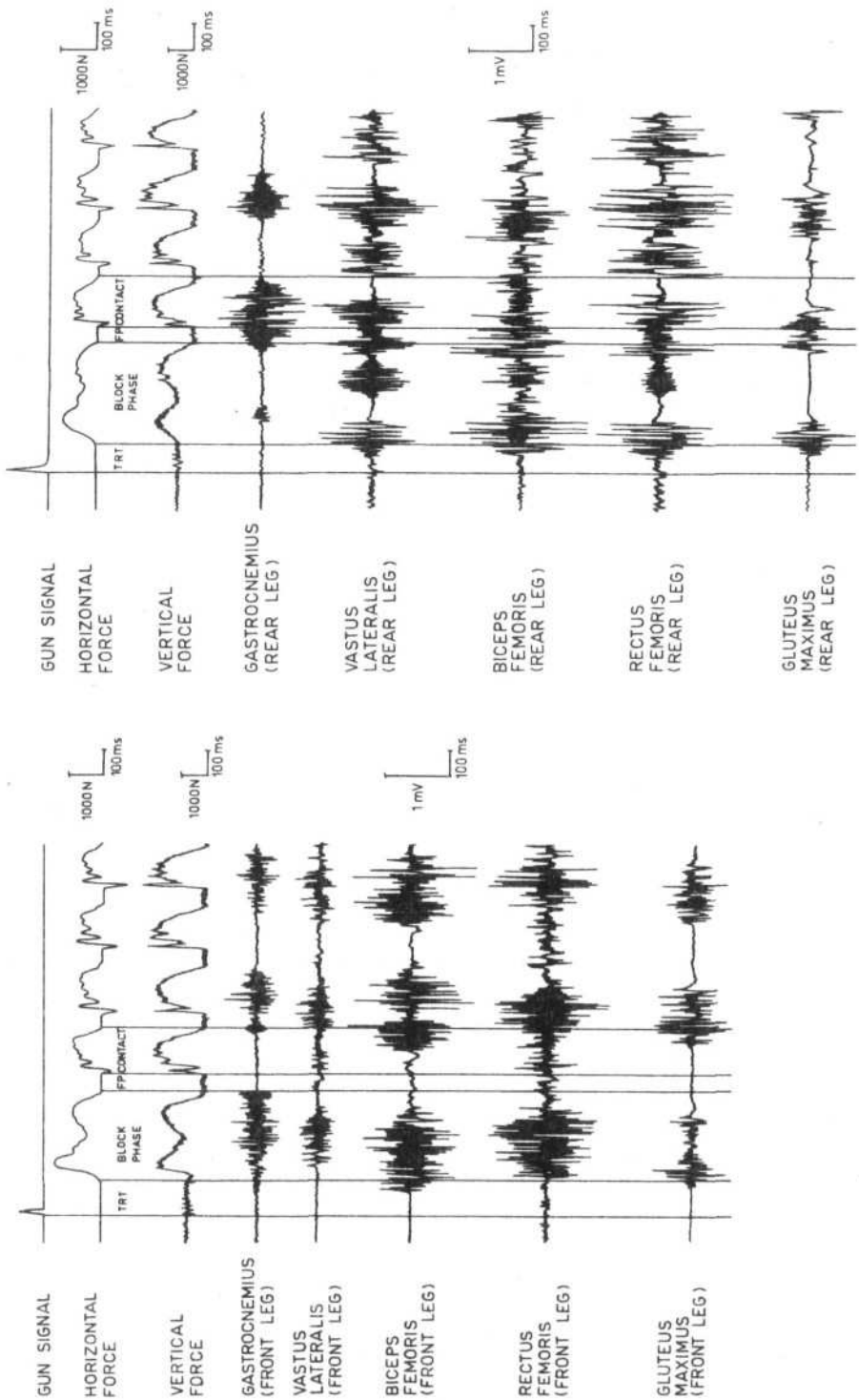


Fig 1. Raw electromyographs of selected muscles in front and rear legs during maximal sprint start of 1 subject, shown together with the ground reaction forces. TRT = total reaction time; FP = flight phase.

## **2. Technique, EMG Activity and Force Production**

### **2.1 Starting Block Phase**

#### *2.1.1 Sprint Start Technique*

'Starting block phase' refers to the time when the sprinter is in contact with the blocks. In the 'set' position, the height of the centre of gravity of sprinters varies from 0.61 to 0.66m, while the horizontal distance from the starting line varies from 0.16 to 0.19m (Baumann 1976; Mero et al. 1983). These values indicate that the blocks and body segments of a sprinter can be positioned so that the centre of gravity of the body is high and near the starting line at the beginning of the run. Segmental lengths affect the height of the centre of gravity and the arm strength of the athletes affects the horizontal distance from the starting line (the stronger the arms the shorter the distance; more forward lean) [e.g. Baumann 1976, 1979; Hoster 1981; Hoster & May 1978; Menely & Rosemier 1969; Mero et al. 1983].

#### *2.1.2 EMG Activity*

Muscle activation patterns described by Mero and Komi (1990) showed considerable individual variances at the beginning of start (see also fig. 1). The gluteus maximus muscle of the rear leg reaches maximum integrated EMG output during the first 50 msec with activity levels decreasing subsequently. The results provide support for the concept that this muscle is very active at the beginning of force production during the block phase. The biarticular biceps femoris muscle of the rear leg has an initial peak integrated EMG at the end of block contact. Both the vastus lateralis and rectus femoris muscles of the rear leg have their initial peaks at the beginning of force production in the blocks. Gastrocnemius muscle activity starts later, during the reaction phase, but the activity level is partly related to the position of the rear foot in the block. If the first spikes are in track, gastrocnemius muscle activity begins earlier.

The duration of force production by the front leg is nearly the same as that during the total block phase, because the front leg produces force from

the beginning of the total force production to the end of the block phase (e.g. Baumann 1979). The gastrocnemius muscle is the first of the 5 muscles studied to become activated. Two peaks are observed during the block phase with the higher occurring at the end of that phase. The peaks occur at the end of both rear leg and front leg contact with the blocks. The rectus femoris and vastus lateralis muscles increase EMG activity during the block phase until the last stages, when it declines. Electrical activity in the biceps femoris muscle of the front leg peaks at the beginning of force production. In this muscle, motor time could be measured in every subject emphasising the importance of this muscle during the early stages of the sprint start. In addition, the gluteus maximus muscle of the front leg displays the maximum integrated EMG value at the beginning of force production in the blocks.

#### *2.1.3 Force Production*

The duration of force production in the blocks ranges from approximately 0.34 to 0.37 seconds in male sprinters (e.g. Baumann 1976; Mero 1988; Mero et al. 1983). The rear leg produces force for only of 45% of the block phase on average (Mero & Komi 1990). In order to get more pre-tension in calf muscles, thenar muscles (the first spikes) of both feet should be positioned on the track. With prestretched calf muscles it is possible to get a more efficient start movement. If the body mass is centered more on the legs than on the arms, pre-tension may be increased. After the gun signal knee and hip angles in both legs begin to increase when producing force, but ankle angles initially decrease. This kind of joint and muscle function supports the possibility of performance enhancement through a stretch-shortening cycle which improves force production (see Komi 1984).

Measurement of force production in the blocks indicates that elite sprinters produce greater forces and have greater block velocity (the horizontal velocity of the centre of gravity of a sprinter during the last contact moment in the blocks) than the less skilled sprinters (table I). Block velocity has ranged from 2.90 to 3.94 m/sec in male sprinters (Bau-

**Table 1.** Reaction force production in the blocks in various sprint groups (means)

Variable	Men <sup>a</sup> (n = 12)	Men <sup>b</sup> (n = 8)	Men <sup>b</sup> (n = 8)	Women <sup>c</sup> (n = 10)
100m record (sec) [hand time]	10.35	10.80	11.50	11.69
Duration of force production (sec)	0.369	0.361	0.368	0.390
Horizontal force production				
maximal force (N)		1186	898	
average force (N)		650	531	
impulse (N · sec)	263	234	195	156
power (W/kg)		12.7	9.4	
Vertical net force production				
maximal force (N)		958	683	
average force (N)		641	484	
impulse (N · sec)		231	178	213
power (W/kg)		4.1	3.5	
Resultant force at the moment of maximal horizontal force				
force (N)		1555	1175	
direction from horizontal (°)		40	38	
Average lateral force (N)		37	78	
Bodyweight (kg)	73.6	74.7	77.6	54.4
Proportion of bodyweight on the legs in the 'set' position (%)	Under 28.0	57.4	59.5	30.0
Block velocity <sup>d</sup> (m/sec)	3.60	3.22	2.94	2.87

a Baumann (1976).

b Mero et al. (1983).

c Baumann (1979).

d The horizontal velocity of the body centre of gravity at the moment of the last contact of the front foot in the blocks.

mann 1976; Coppenolle et al. 1989; Mero 1988; Mero et al. 1983) and from 2.54 to 2.87 m/sec in female sprinters (Baumann 1979). No data are available from major championships.

## 2.2 Acceleration Phase

### 2.2.1 Technique

After take-off from the blocks, a runner accelerates by increasing stride length and stride rate. The length of the acceleration phase is 30 to 50m in top sprinters during a 100m race (e.g. Moravec et al. 1988; Volkov & Lapin 1979). The position of the body centre of gravity with respect to the first contact point on the ground changes during the first few strides. At the beginning of the first two contact phases, it is ahead of the contact point. By the beginning of the third contact phase, the

body centre of gravity is already behind the contact point on the ground (Mero et al. 1983). From the first ipsilateral contact phase forwards the body centre of gravity falls during the early part of contact (braking phase) and rises during the last part of contact (propulsion phase). The contact phase can be divided into braking and propulsion phases using either the movement of the body centre of gravity or the negative and positive horizontal reaction forces (see Luhtanen & Komi 1978; Miller 1983).

The decrease in running velocity during the braking phase of the first 2 strides out of the blocks ranges from 3.0 to 11.3% in different sprint groups (Mero 1988; Mero et al. 1983). During the accelerative phase of the velocity-time curve stride length, stride rate and flight time increase and approach values reported for maximum speed (or

other constant speed). Contact time decreases during the acceleration phase (e.g. Moravec et al. 1988).

### 2.2.2 EMG Activity

High integrated EMG activity during acceleration has been reported by Mero and Peltola (1989). In that study 2 male sprinters ran a 100m simulated race and in the acceleration phase there was a 4.8% higher maximal integrated EMG activity during contact than in the maximum constant speed phase. This may imply that neural activation of a sprinter achieves its maximum in the acceleration phase. Some details, of the EMG activity during the accelerative stride are illustrated in figure 1 (Mero & Komi 1990), but EMG activity during the stride is discussed in section 2.3.2.

### 2.2.3 Force Production

Despite the location of the body centre of gravity with respect to the first contact point on the ground, negative horizontal force is observed in the first contact after the blocks, probably caused by the leg moving forwards. This suggests that in sprint running, all contacts are similar with braking and propulsion phase, although the ratios are different. The first braking phase (22 msec) of the male sprinters was only 12.9% of the total duration (193 msec) of contact (Mero 1988), whereas at maximum constant speed, it has been reported to be about 43% (see e.g. Mero & Komi 1987b). The braking phase thus increases as a proportion of total contact during the acceleration phase. Average forces in the first braking phase are very small in both horizontal (–153N) and vertical (148N; net force) directions, but in the propulsion phase the respective values (526N and 431N) are clearly larger (Mero 1988). The average forces in the first braking phase constituted about 44% (horizontal) and 11% (vertical) of the respective values during maximal constant speed (e.g. Mero et al. 1987). Average vertical force in the propulsion phase is similar to the braking phase, but the horizontal force during the first propulsion phase is about 46% greater. These values provide a good description of the pattern of force production during the early acceler-

ation phase. The force is produced for a long period and the average propulsive force is large.

In maximal constant sprinting, in contrast, the contact phase is very short and the impact forces are very large. The high correlation coefficient ( $r = 0.74$ ;  $n = 8$ ; Mero 1988) between the propulsive force and running velocity during the first contact after the blocks further emphasises both the character of the propulsion phase and the importance of strength during the acceleration phase of sprinting.

## 2.3 Constant Speed Phase

Constant speed can be submaximal, maximal or supramaximal. Supramaximal speed can be achieved with methods such as a tail wind, downhill running (e.g. Leierer 1979), towing horizontally (e.g. Bosen 1979; Mero & Komi 1985) or both horizontally and vertically (e.g. Glaspey 1980; Mero et al. 1987) and high-speed treadmill running (Singh et al. 1976).

### 2.3.1 Technique

Running velocity is the product of stride rate and stride length. In studies where the same subjects ran at different speeds both stride rate and stride length increased with increasing speed (Luhtanen & Komi 1978; Mero & Komi 1986). These increases are primarily linear for speeds up to 7 m/sec. At higher speeds there is a smaller increment in stride length and a greater increment in stride rate for a given increase in velocity. This means that at high speeds runners increase their velocity by increasing stride rate to a relatively greater extent than stride length. At maximal velocities of male sprinters, it is suggested that stride rate has a more decisive role than stride length (e.g. Mero et al. 1981; Tabatschnik et al. 1978). The highest values of stride rate have been reported to be above 5Hz at maximal constant speed while during the same phase stride length has ranged from approximately 2 to 2.6m (e.g. Mann & Herman 1985; Mero et al. 1982; Moravec et al. 1988). The highest constant velocity (12.05 m/sec) was measured during a 100m race (Ben Johnson & Carl

Lewis in Seoul) between the 50 and 60m distance (Dick 1989).

Hoffman (1964) conducted an extensive study of sprint running analysing 56 of the top male sprinters in the world. Correlations between maximal stride length (measured between 50 and 60m in the 100m race) and body height and leg length were high ( $r = 0.59$  and  $0.70$ , respectively). Similar relationships ( $r = 0.63$  and  $0.73$ ) were reported by Hoffman (1967) in 23 world-class female sprinters. There are no sex differences regarding stride rate. However, men have a longer stride length which helps explain the difference in running velocity between men and women (e.g. Mero & Komi 1986; Mero et al. 1988; Moravec et al. 1988).

In supramaximal sprint running with horizontal towing (Mero & Komi 1986) velocity was 8.4%, stride rate 6.9% and stride length 1.5% greater than in maximal running. When towing was simultaneously horizontal and vertical, stride rate was unchanged but stride length clearly increased (Mero et al. 1987). During stimulated sprint running (horizontal towing and simultaneously a high signal frequency of about 110% of the supposed stride rate being sent into the ears of the runners) both stride rate and stride length could be significantly increased (Mero & Komi 1987b). It seems then that in supramaximal sprint running using a horizontal towing system it is possible to run at a higher stride rate than in voluntary maximal running. These data suggest that supramaximal sprinting can be an additional training stimulus for the neuromuscular system during training.

In maximal sprinting flight time ranges from approximately 0.120 to 0.140 second (e.g. Kunz & Kaufmann 1981; Mero et al. 1982; Moravec et al. 1988). Flight time was longer in supramaximal than in maximal sprinting with horizontal towing, with a simultaneous increase in stride length (Mero & Komi 1985) but when stride length did not increase (but stride rate increased) flight time was also unchanged (Mero & Komi 1986). Contact time has been reported to decrease significantly as running velocity is increased. Luhtanen and Komi (1978) divided the contact phase into braking and propulsion phases, defined as the periods when the

centre of gravity of the body moved either downward (braking) or upward (propulsion). Relative times for both phases decreased similarly across a speed range of 3.9 to 9.3 m/sec. In maximal sprinting, the contact time is very short, ranging from about 0.080 to 0.100 sec (e.g. Kunz & Kaufman 1981; Mero et al. 1982; Moravec et al. 1988). Contact time can be shortened as a result of supra-maximal sprinting (Mero & Komi 1985).

Vertical peak-to-peak displacement of the centre of gravity of the body during the stride has been shown to decrease with increased running speed (e.g. Cavagna et al. 1971; Luhtanen & Komi 1978). Mero et al. (1982) observed vertical displacements of 0.047, 0.050 and 0.062m for 'good' (9.86 m/sec), 'average' (9.60 m/sec) and 'poor' (9.24 m/sec) male sprinters, respectively. A number of studies have found that at constant speed there is a decrease in velocity of the centre of gravity of the body following initial foot impact. Then, during the subsequent propulsion phase, there are velocity increases. Cavanagh and LaFortune (1980) found a decrease of 0.18 m/sec in running velocity during the braking phase at 4.47 m/sec, which was followed by an increase of 0.27 m/sec during the propulsion phase. Velocity at toe-off was greater than that at touchdown. The researchers hypothesised that the air resistance would probably account for the decreases in running velocity during flight which would maintain a constant average velocity. In maximal running by male sprinters, Mero et al. (1982) reported decreases of 0.39 m/sec for 'good' sprinters, 0.43 m/sec for 'average' sprinters, and 0.53 m/sec for 'poor' sprinters. Results from the 'good' sprinters are consistent with those of the top male and female sprinters (Mero et al. 1988). The primary reason for the decrease in running velocity is the horizontal distance between the first contact point and the centre of gravity of the body at touchdown (e.g. Deshon & Nelson 1964; Kunz & Kaufman 1981; Mero et al. 1982). During this time the centre of gravity of the body moves downward and horizontal running velocity decreases. This is a critical point in stride structure for reasons of running economy.



### 2.3.2 EMG Activity

Running requires a complex sequencing of muscle activation in the body. In the leg muscles, EMG activity has generally been found to increase with increased running speed (Hoshikawa et al. 1973; Mero & Komi 1986). These experiments used the same subject groups running at different constant speeds. In the propulsion phase, EMG activity is markedly lower than during the braking phase (Dietz et al. 1979; Komi 1983; Mero & Komi 1986). This may be partly related to increased recoil of elastic energy during the propulsion phase (see e.g. Cavagna et al. 1971; Luhtanen & Komi 1980; Mero & Komi 1986; Williams & Cavanagh 1983). An example of muscle activation during a stride at maximal speed is presented in figure 2.

In sprinting, there is high activity in the leg musculature before contact (Dietz et al. 1979; Mero & Komi 1987a). When this preactivity is expressed in relative values (calculated from the maximal contact values) no significant differences between speeds or sexes are observed (Mero & Komi 1987a). Preactivity EMG values (mean of 5 leg muscles) range from 50 to 70% of maximum contact integrated EMG. At the beginning of the contact phase large impact forces occur. It is important therefore that the leg extensor muscles are highly activated and stiff prior to, and at the moment of, impact. The electromechanical delay (the time between the detectable electric activity and effective mechanical response) of a muscle has been reported to range between 20 and 100 msec (see e.g. Komi 1984). The ground contact should take place after this electromechanical delay. It has been proposed (Melvill-Jones & Watt 1971) that preactivation is preprogrammed and stimulated from higher centres of the central nervous system.

During contact, the peak ground reaction forces take place 10 to 40 msec after the first ground contact (Mero & Komi 1987a). Since these peak forces exist so soon after the beginning of ground contact the stretch reflex system may not have enough time to become fully active (see e.g. Dietz et al. 1979). As a result, high preactivation plays a major role by increasing stiffness in muscles to resist impact. It may be suggested that both the high preactivation

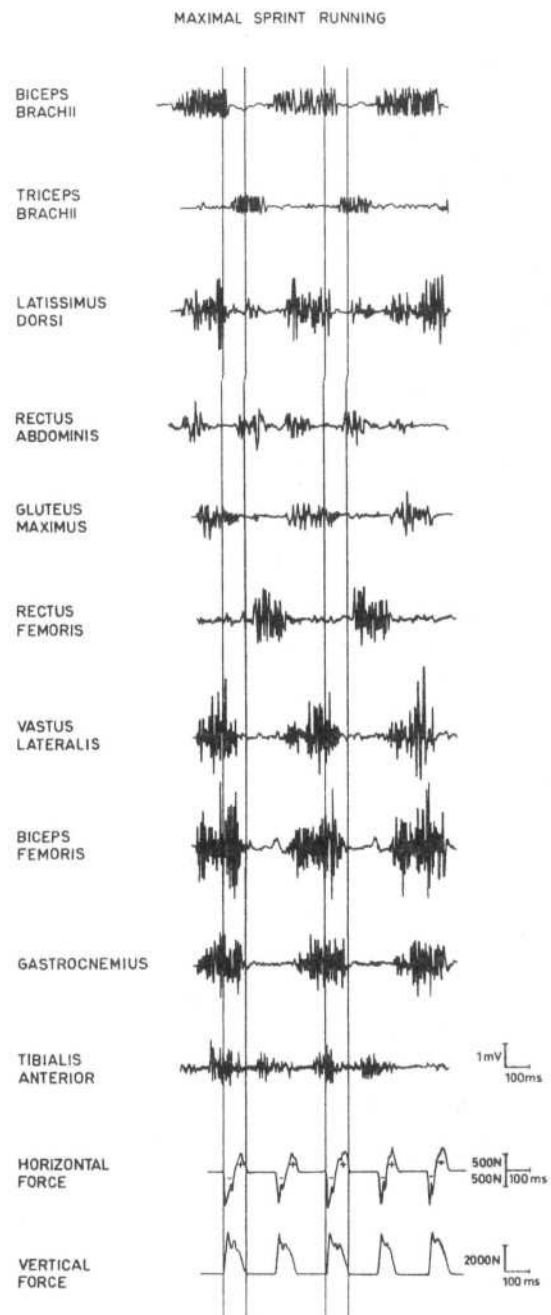


Fig. 2. Raw electromyographs of selected muscles during stride at maximal speed of 1 subject, shown together with ground reaction forces.

tion and reflex-potential after impact play an important role in maintaining the stiffness in the muscle upon and immediately following impact. It may also be possible that greater activation of muscle spindles during stretching in supramaximal compared to maximal running causes the reflex potentiation to be greater (Mero & Komi 1987a). Moreover, energy is transferred by the elastic elements from the braking phase to the propulsion phase and utilisation of the elastic properties has been shown to be important in increasing explosive force production during contact (e.g. Cavagna et al. 1971; Komi & Bosco 1978).

During maximal sprint running, peak activity of the leg extensor muscles occurs during the braking phase of ipsilateral contact (leg on the ground). Thereafter, integrated EMG begins to decrease towards the end of the propulsion phase. For the 2-joint rectus femoris muscle, the situation is more complex. It can be suggested, however, that at the end of and after ipsilateral contact, the rectus femoris muscle acts eccentrically due to extension at the hip joint and flexion at the knee joint. In the middle of the next flight phase, the muscle begins to shorten while flexing the thigh. It is not very active in extending the shank before ipsilateral contact. The rectus femoris muscle seems to be more important as a hip flexor in sprint running than as a knee extensor (Mero & Komi 1987a). The biceps femoris and gastrocnemius muscles are fairly active during the ipsilateral propulsion phase, and seem to play a primary role in the propulsion phase of sprint running (Mero & Komi 1987a).

There is a significantly greater integrated EMG in the gastrocnemius muscle (women) and the vastus lateralis muscle (men) in ipsilateral contact in supramaximal sprinting than in maximal sprinting (Mero & Komi 1987b). In the same study, the significant correlation ( $r = 0.64$ ) between the relative changes of integrated EMG in the braking phase and stride rate between the maximal and supramaximal runs suggests that increased neural activation in the supramaximal effort has a positive effect on stride rate. This supramaximal method could have benefits in sprint training by adapting human neuromuscular performance to a higher

stride rate level. In the experiments by Mero and Komi (1987a) EMG activity immediately after contact increased with increased speed, with the exception of supramaximal running. Horizontal towing probably helped the subject push the body forward because both force production and EMG activity were reduced when compared to maximal running. After take-off in maximal and supramaximal sprinting, however, when the heel is moved towards the hip, there is not much EMG activity in the biceps femoris and gastrocnemius muscles. This flexion of the shank must be caused by external forces, probably generated as reaction forces during contact, and by the residual muscle tension due to the relaxation time of the muscles (Bigland-Ritchie et al. 1983).

Minimum activity in leg muscles has the same profile as activity after contact (postactivity) with changes in running speeds (Mero & Komi 1987a). When postactivity is diminished in supramaximal running, minimum activity is also diminished because of towing. Minimum activity of leg muscles usually occurs during flight.

### 2.3.3 Force Production

Researchers have employed many variables to analyse force-time curves during the ground phase, including horizontal, vertical and mediolateral ground reaction forces. During constant velocity sprint running, increases in horizontal and vertical force production with increasing running speed have been reported (Mero & Komi 1986). Data on mediolateral forces, however, have only been reported for slow running and only small changes have been found with increasing speed, with typical values being less than 0.3 times bodyweight (Cavanagh & LaFortune 1980; Roy 1982).

The average resultant braking force increased with increased sprinting speed (Mero & Komi 1986). At submaximal speed ( $4.95 \pm 0.46$  m/sec), this force (including bodyweight) reached an average value of  $1314 \pm 59$  N for the male sprinters and  $1212 \pm 114$  N for the female sprinters (at speed of  $4.75 \pm 0.57$  m/sec). With horizontal towing resultant forces were  $2257 \pm 55$  N for men and  $1733 \pm 71$  N for women (sprinting at  $10.91 \pm 0.34$  and

9.62  $\pm$  0.23 m/sec, respectively). The average resultant propulsion force increased as speed increased from the lowest submaximal speed to maximal speed. Force decreased, however, at supramaximal speed. The decrease is probably a result of the towing system. The lowest force recorded was 1210  $\pm$  70N for men and 1100  $\pm$  73N for women, and the highest values (maximal running) were 1778  $\pm$  76N and 1320  $\pm$  63N, respectively. The differences between sexes were significant and the 'good' male sprinters differed significantly from the 'poor' male sprinters.

Significant correlations in the maximal run were found between the average net resultant force in the propulsion phase and velocity and stride length. The observed difference of 10.6% in stride length during the maximal run between men and women is consistent with other findings (e.g. Mero et al. 1988) and can be explained by the greater reaction forces in the men.

Peak forces occurred during the braking phase and were highest in the supramaximal run. Peak vertical force was 4.6 times bodyweight for men and 4.2 times bodyweight for women. Earlier, Payne (1983) reported data from a single subject showing a peak force of approximately 5.5 times bodyweight during sprint running (a rearfoot striker; average velocity of 9.50 m/sec). Peak values are affected by the foot position at ground contact; most sprinters, such as those in the study by Mero and Komi (1986), make the first contact high on the ball of the foot, which tends to attenuate the so-called 'heel spike'.

Maximal sprint running is compared to supramaximal run in table II which presents detailed results on force production. Supramaximal running was achieved by the stimulated horizontal towing system (Mero & Komi 1987b) which increased both stride length and stride rate. Differences in force production and stride times are clear.

In sprint running, there are usually large vertical force components in both contact phases while horizontal forces are small. The braking horizontal force and braking time should be very small to avoid loss of velocity during the impact phase. The direction of resultant force is similar in the braking

phase but in the propulsion phase it is more horizontal in supramaximal than in maximal sprinting. The goal is to direct the resultant force as vertical as possible in the braking phase and as horizontal as possible in the propulsion phase.

Elasticity of the contact leg has been evaluated from film data using an apparent spring constant value (Luhtanen & Komi 1980). Spring constant value is great when the resultant force at the centre of gravity is great, the peak-to-peak oscillation and the horizontal displacement of centre of gravity are small and the contact time is short. Using this value, the combined elasticity of muscles, tendons and bones of the support leg can be evaluated. Spring constants are high during braking phase and very low during propulsion (Luhtanen & Komi 1980; Mero & Komi 1986). In braking, the values increase when running velocity increases to maximum. At supramaximal speed, however, they decrease (Mero & Komi 1986). This decrease is associated with the descent of the centre of gravity during impact, which is greater with the towing system. These results may imply that the high supramaximal running velocities are too great for the support leg to resist the impact without falling. The values in propulsion are low and do not change with increasing speed. No clear differences between sexes were reported in the spring constant values.

#### 2.3.4 Achilles Tendon Forces in Running

While the force platform recording gives information on the ground reaction forces affecting the whole mass of the runner, direct force measurements on tendons could characterise how individual muscles are loaded in different phases of the ground contact. The Achilles tendon has proven useful for this purpose and special buckle transducers can be surgically implanted around the tendon under local anaesthesia (Komi et al. 1987). After the wound has been sutured the subject is free to perform normal activities ranging from slow walking to fast sprinting. The data obtained have indicated that the peak to peak Achilles tendon force increases with the increase in running velocity up to 6 m/sec, above which it stays the same

**Table II.** Ground reaction net average forces in maximal and supramaximal running of 6 male sprinters. Supramaximal speed was achieved by a stimulated towing system (Mero & Komi 1987b)

Variable	Maximal sprint running	Supramaximal sprint running	p <
Running velocity (msec)	9.96	10.82	0.001
Contact time (msec)	94	92	ns
Flight time (msec)	120	125	ns
Braking phase (msec)	39	45	0.05
horizontal force (N)	445	559	0.05
vertical force (N)	1707	2044	0.01
resultant force (N)	1766	2122	0.001
direction of resultant force from horizontal (°)	75	75	ns
horizontal power (W/kg)	59	81	0.001
Propulsion phase (msec)	55	47	0.05
horizontal force (N)	312	334	0.05
vertical force (N)	797	621	0.05
resultant force (N)	857	709	0.01
direction of resultant force from horizontal (°)	68	61	0.05
horizontal power (W/kg)	42	48	0.01

or slightly decreases at higher speeds (Komi 1988). In some individuals the peak Achilles tendon force can reach as high as 9kN (12 to 13 times body-weight). The rate of development of Achilles tendon force during the braking phase increases linearly as running speed increases and it can reach a maximum value 175 kN/sec. The shape of the Achilles tendon force-time curve during ground contact is like that of a bouncing ball.

Utilising the method of Grieve et al. (1978) to estimate the total muscle length changes during contact, Achilles tendon force data can be used to examine the force-length and force-velocity curves of the triceps surae muscle. This analysis has indicated that the measured muscle group demonstrates force performance potentiation particularly in the concentric phase of the curves. Much of this force potentiation takes place as a recoil phenomenon, because the gastrocnemius and soleus muscles become inactive before the end of the concentric phase. Thus, in running, where stretch-shortening cycle is typical for the triceps surae muscle, the stretching phase is characterised by a small change in length and high level of stiffness. This enables the muscles to resist high impact loads

and to modify the conditions for good performance potentiation in the subsequent concentric action.

## 2.4 Deceleration

### 2.4.1 Technique

In short sprint running (especially 100m) the phases of the velocity curve can easily be distinguished. In the deceleration phase, the loss of velocity from peak during a 100m race at major championships ranges from 0.9 to 7.0% (Mero 1985; Moravec et al. 1988). The interindividual range is great (from 0.0 to 9.3%) indicating great variation in performance capacity. Stride rate decreases, but stride length slightly increases during deceleration (e.g. Gundlach 1962; Moravec et al. 1988; Mero & Peltola 1989). Both contact and flight times increase at the end of the race, and increases in the braking distance, vertical descent of the body centre of gravity and velocity loss during braking are also observed (Moravec et al. 1988; Mero et al. 1988; Mero & Peltola 1989). The shape of the velocity-time curve during a long sprint run (200m, 400m) is affected by many variables, such as tactics, wind and the utilisation of energy sources. The interpretation of the deceleration is therefore more dif-

difficult than in short sprint running (e.g. Bates & Haven 1974; Mero et al. 1988; Mero and Peltola 1989; Sprague & Mann 1983).

#### *2.4.2 EMG Activity*

Only one study is available concerning EMG activity during the deceleration phase of sprint running (Mero & Peltola 1989). The EMG activity pattern in 5 leg muscles was similar to that in the phase of constant velocity. The average maximal activity of the muscles during a stride decreased 6.8% during a simulated 100m race. The maximum was observed during acceleration with decreases of 4.8 and 2.0% observed for the phases of the constant and deceleration speeds, respectively. During a simulated 400m race, peak constant velocity occurred between the 50m and 100m mark and decreased thereafter, on average, 15.0% to the end velocity. Concomitantly, the maximal EMG activity of the 5 leg muscles, respectively, increased 23.4%. These results would suggest that during the first part of the 400m race, the runner did not maximally recruit his neuromuscular system in order to sustain his submaximal speed. He must, therefore, increase the role of nervous system trying to compensate for the decrease in speed.

#### *2.4.3 Force Production*

No research data are available concerning ground reaction forces during the deceleration phase.

### *3. Neural Factors*

In voluntary contractions, the central nervous system regulates muscle force by changing the number of recruited motor units. Additional force regulation is achieved by varying the individual motoneuron firing rates. In sprint running it is important to recruit as many fast motor units as possible, since these units are more suitable for fast locomotion. The two main groups of motor units known to exist in human neuromuscular system are slow (type I) and fast (type II) motor units which have functionally and structurally different kinds of motoneurons. The motor units which contain

the respective different kinds of muscle fibres have been classified according to their contraction time and fatigue resistance (see Eberstein & Goodgold 1968; Garnett et al. 1978).

As briefly discussed earlier in this review, there is EMG activity in leg muscles before, during and after contact in the course of sprint running. Activity prior to ground contact increases stiffness in the leg muscles, which is needed to resist high impact loads during the initial contact stages. Those muscles involved in the contact phase, produce significant increases in EMG shortly after ground contact, which corresponds to a short latency spinal stretch reflex. On the other hand, at high supramaximal speeds, inhibition by structures such as the Golgi tendon organs, may surpass the 'potentiating' effects of the muscle spindle. In the test runs, supramaximal velocities have been high, but the inhibitory role of the Golgi tendon organ cannot be estimated. It can be suggested, however, that both the high preactivity and the reflex potentiation after impact may play an important role in maintaining the high muscle stiffness at and immediately following impact. The probable increased muscle stiffness during the braking phase can favour the conditions for a good bouncing action during sprint running (e.g. Komi 1983).

Motor nerve conduction velocity has been demonstrated to be faster in athletes trained for speed strength events than in athletes competing in other events (Lehnert & Weber 1975). It has been suggested that both genetic and environmental factors influence differences in nerve conduction velocity (Kamen et al. 1984). Lastovka (1969) suggested that training may increase nerve conduction velocity of the posterior tibial nerve. Consequently, maximal and supramaximal sprint running may have acute and/or long term training effects on the nervous system. If this is true, then an increased stride rate combined with greater rate of force production during the braking phase in supramaximal sprinting might be used as an effective training stimulus. The work of Edds (1950) and Wedeles (1949) who noted an increase in motor nerve axon diameter due to training further supports these suggestions. Andersson and Edström (1957), on the other hand,

found a decrease, but there are other reports that show no changes in axon diameter (e.g. Tomanek & Tipton 1967). Since nerve axon diameter is directly related to nerve conduction velocity (Arbuthnott et al. 1980; Paintal 1973; Waxman 1980), any change in diameter would result in a concomitant change in nerve conduction velocity.

There is a clear need for further research work concerning neural factors in sprint running, to enhance our understanding of the various mechanisms of neuromuscular system and develop new training methods.

#### **4. Muscle Structure**

Many studies (Costill et al. 1976; Gollnick et al. 1972; Mero 1987; Mero et al. 1981) show that the number and cross-sectional area of type II fibres are high in the leg extensor muscles of male and female sprinters. The current understanding is that muscle fibre composition is genetically based (e.g. Komi et al. 1977) and is difficult to change with training. Muscle fibre volume (area), however, can be increased with training and the specificity of training determines which fibre type is most affected (e.g. Coyle et al. 1981; Hakkinen et al. 1985). Therefore, it is logical that sprinters have greater type II than type I fibre areas in their leg extensor muscles because their training consists primarily of fast repetitive movements. Block velocity and running velocity in the phases of acceleration and maximum constant speed directly and significantly correlate with the proportion of type II fibre in the vastus lateralis muscle (Mero et al. 1981, 1983). Also, the final sprint performance (100m record) correlates strongly with this composition percentage (Mero et al. 1981). Mero (1987) found significant positive correlations between the proportion of type II fibres in the vastus lateralis muscle and average net resultant propulsion force in the maximal run as well as maximal running velocity.

These findings support the conclusion that muscle fibre characteristics are related to the selection of talent and the training-induced effects in sprint running. Because development in maximal running velocity during sprint training is very lim-

ited, it is important to discover potential talent (e.g. a high proportion of type II fibres) in the training system. On the other hand, muscle fibre area measurements give additional information on training-induced effects (e.g. strength training compared to type II fibre area).

#### **5. Other Factors**

The modern sprinting shoes on tartan type surfaces have spikes which are from 5 to 7mm in length. Unfortunately, there are no relevant research data available concerning the influence of type of spike shoes or other sport clothes on sprinting.

There are also some factors external to the runner such as ground surface and air resistance but they are not included in this review. Energetics is an important factor influencing the performance of the runner but it is also beyond the scope of this report.

#### **6. Economy of Sprint Running**

A commonly used method to establish differences between individuals in the economy of physical effort is to evaluate the oxygen consumed while performing a particular exercise. This approach is useful during a steady-rate exercise in which the oxygen consumed during the activity closely matches the energy expended. The economy of distance runners has been evaluated with this approach, but it is difficult to evaluate sprint running because of the great contribution of the anaerobic processes. Another approach to evaluate the relationship between input and resulting output in running is to try to compute actual mechanical efficiency. This provides an indication of the percentage of total energy expended that can produce external work. This is also very difficult in sprint running because of calculations of the exact work and input of energy. Some investigations have, however, tried to evaluate either economy or efficiency of (sprint) running and those are reviewed below.

In distance running variations from the freely

chosen stride length have been shown to result in increased metabolic energy cost (Cavanagh & Williams 1982; Hogberg 1952; Knuttgen 1961). Another parameter which is often related to either economy or efficiency of running is the vertical oscillation of the total body centre of gravity. It is typically hypothesised that the more efficient runner is characterised by smaller vertical movements of the body (e.g. Cavanagh et al. 1977; Gregor & Kirkendall 1978; Slocum & Bowerman 1962). There are no sprint results available but these main variables probably have a decisive role in the economy of locomotion in sprint running. Other variables associated with economy of running, are details of sprint stride structure (e.g. Deshon & Nelson 1964; Kunz & Kaufman 1981; Mero et al. 1982), ground reaction forces in distance running (e.g. Williams 1980) and sprint running (e.g. Mero & Komi 1987a), elasticity in sprint running (e.g. Cavagna et al. 1971; Mero & Komi 1986), footwear in distance running (e.g. Frederick et al. 1982) and air resistance in sprint running (Davies 1980). Especially, the use of eccentric actions (elastic elements) in stretch-shortening cycle is economical in terms of high mechanical efficiency compared to mechanical efficiency of 14 to 18% during pure concentric work (Aura & Komi 1986). The values of mechanical efficiency during the propulsion phase of the stretch-shortening cycle when running at low or moderate speeds have been recently reported. Cavagna and Kaneko (1977) demonstrated that efficiency increases with increasing speed (1.7 to 9.2 m/sec) from 45 to 70%. However, relatively constant efficiency values ( $55.0 \pm 12.7\%$ ) in a range of speeds (1.9 to 6.1 m/sec) have also been presented (Ito et al. 1983). Values above those in normal pure concentric work result from the events in the braking phase. Mechanical efficiency of the total running performance was evaluated by Kaneko et al. (1985). Velocity ranged from 4.0 to 9.5 m/sec and mechanical efficiency decreased from about 64 to 17%. It was higher in the distance runners than in the sprinters at speeds lower than 7 m/sec, but this relationship tended to reverse at higher velocities showing specificity of training.

A linear relationship between integrated EMG

and energy expenditure has been reported by Bigland-Ritchie and Woods (1984), indicating that EMG measurements can be used to evaluate economy of performance. The ratio (average net resultant force/integrated EMG absolute value) decreased in the braking and propulsion phases with increased sprinting speeds (constant speeds ranging from 5.2 to 10.74 m/sec; Mero 1987). The changes were nonsignificant but may reflect a decreased efficiency during total contact with increased speed. Mero and Peltola (1989) measured maximum and minimum integrated EMG activity of 1 stride in simulated races (100m and 400m) and concluded that they can be used to calculate relaxation of the muscles and finally to evaluate the economy of locomotion. The researchers found that muscular relaxation deteriorated with increasing fatigue during both races especially in curve running of 400m.

Economy of sprint running can also be evaluated by measuring anaerobic energy production (blood lactate levels) while performing submaximal sprints and measuring blood lactate levels (e.g. Föhrenbach et al. 1986). For example, at a given submaximal speed (90%) of sprinting, an athlete with greater economy for movement produces less blood lactate to perform the sprints (for example 3 x 4 x 60m), and thus uses more ATP and creatine phosphate stores and blood pH decreases less. This approach is widely used in practice to evaluate economy of sprint running.

## 7. Conclusions

The major known contributors to the biomechanics of sprint running in all phases of the velocity curve have been presented. Biomechanical variables of sprint running include information on reaction time, technique, electromyographic activity, force production, neural factors and muscle structure. When there is an optimal combination between these variables and external factors such as footwear, ground and air resistance, it is possible to run very economically.

At the beginning of the sprint run, it is very important to produce great force/power and generate high velocity in the block and acceleration

phases. Further research is needed to analyse the contributions of different muscles to force production. During the phase of constant speed, which can be submaximal, maximal or supramaximal, the events just before and during the braking phase are important in increasing explosive force/power and efficiency of movement in the propulsion phase. In the phase of sprint deceleration, there are no research results available concerning force production.

Although there are many biomechanical variables which can be and have been studied separately, the fast and economical sprint running is a complex series of events. It is hoped that this review might give rise to further research in the area of sprint economy. This will be possible because the continued refinements of techniques will lead to methodologies which can better clarify economical aspects. Further research is also needed to better understand the contributions of the nervous system and muscles to force and power production in sprint running. There is much work to be done in this area and careful efforts should be made to further our knowledge.

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