

KINETICS OF SPRINTING

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The fastest means of unaided human motion consists of a maximal effort run; commonly termed sprinting. Due to its direct importance toward success in the running events in track and field, and its component contribution to success in a majority of other sports, much interest has focused upon the movement. Sprinting has been extensively analyzed both quantitatively and qualitatively utilizing numerous kinematic variables. There is a sparsity; however, of kinetic information relating to not only sprinting, but all forms of human locomotion with the exception of walking.

Fenn (1930) pioneered kinetic description of air phase locomotion by mathematically measuring the work done during running. Elftman (1940) expanded upon Fenn's efforts by describing the muscle moments generated about the body joints. Although the results of both studies (same data) were compromised by measurement error, they continue to provide valuable insight into the kinetics of running. Recent investigations into the kinetic aspects of running have focused on the muscle moments generated in the lower limbs due to the applicability of these results. Plagenhoef (1968) presented a brief report on the lower limb moments generated in distance running, while Dillman (1971) investigated a small part of the sprint stride using the moments of the free (recovery) leg.

A concentrated research effort on the kinetics of sprinting was begun in 1979 for two reasons. The first was obvious lack of information on the direct causes of the movement pattern. The most complex problem, that of describing the kinetics of the ground leg during sprint running, was the first area of investigation (Mann, 1980). This effort was followed by an overall description of the kinetics of sprinting (Mann, 1981). Once an understanding of the mechanical and anatomical causes of sprinting had been initiated, the second stage of investigation was undertaken.

Although a voluminous amount of information has been written on the description of sprinting, little has been done on relating these observable kinematic effects to the kinetic causes. This is of critical importance if research in this area is ever to reach a broad application stage. Kinetic results are an excellent measure of sprinting quality, however, the means

to produce such results are available to only a few research centers. Kinematic results are readily available to anyone with video equipment or a practiced eye, however, identifying the important results, and then relating them to their kinetic causes has been, to date, a matter of guesswork. Thus, the second stage of the research on sprinting focused upon identifying those kinematic effects that were related to the critical kinetic causes of success in sprinting. In one approach, kinematic results were statistically related to the kinetic results that were found to be directly related to maximum sprint performance (Mann, Work in progress). In another approach, the changes in the kinematics of sprinting due to fatigue were statistically related to the changes in the kinetic variables (Mann, In press).

The final step of this research entailed applying the results to benefit the skill performance. Filmed results were taken of world class sprinters, in actual competitive situations. Since the situation precluded the ability to obtain results necessary to generate kinetic results, the kinematic results were used to identify strengths and weaknesses in each performer's sprinting motion.*

Although the research on sprinting has progressed to the application stage, investigation continues on all stages of the research sequence. Additional data continue to modify knowledge on the basic movement patterns, as well as the critical movement contributors to successful performance. The following discussion will summarize the current state of the research.

The Basic Kinetic Patterns

The kinetic parameter used to investigate sprinting was dominant muscle force (moment). In interpreting muscle moment, it must be emphasized that the results indicate the muscle groups that are dominating the activity. Conclusions can be reached regarding the critical muscle action; but, due to the nature of the results, exclusive muscle group activity cannot be ascertained.

In describing the activity, the sprint stride was divided into two kinematic phases; the air phase and the ground phase. The air phase began at toe-off and terminated with foot-strike. The ground phase completed the stride as it progressed from foot-strike to toe-off. Within the two phases, the stride was further divided kinetically using the points of moment direction change at phase endpoints.

The average moment patterns generated about the ankle, knee, and hip are shown in Figures 1, 2, and 3. The Figures also show the range of pattern magnitudes, which were affected by differences in both subject height (direct) and weight (direct). As the Figures indicate, both the ground and air phases were divided into kinetic sub-phases of muscle moment indicating flexor or extensor dominance. Finally, the moment patterns of the arms (at the shoulder and elbow) were also investigated, however, since none of the

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results have yet to show significance regarding the success of sprinting performance, they are not included.

The kinetic results shown in Figures 1, 2, and 3 reveal a great deal about how the body is propelled in a maximum effort sprint. The muscle moment dominance at the ankle (Figure 1), during the air phase, indicates that the total moment associated with muscular activity is essentially zero. This indicates that the muscular activity during this phase is either balanced (static contraction) or virtually non-existent. At foot-strike, the plantar flexors are rapidly employed to begin the task of halting the negative (downward) vertical velocity of the body through eccentric contraction about the ankle. Once this goal has been achieved, the role of the plantar flexors becomes one of generating positive vertical and positive (forward) horizontal velocity to project the body into the impending air phase through

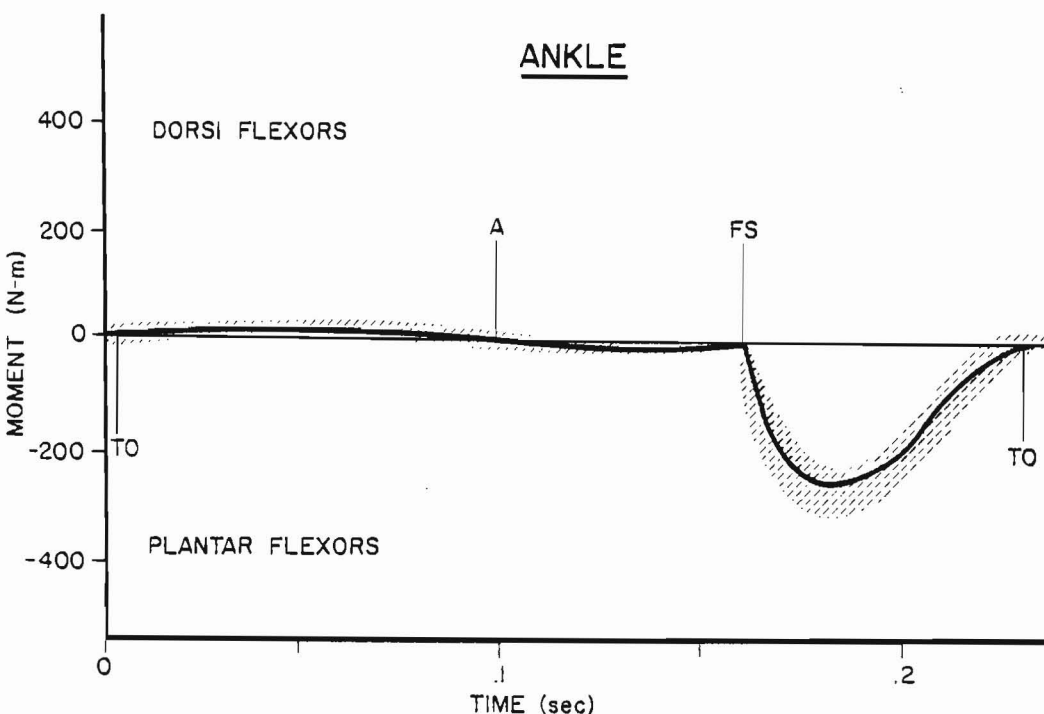


Figure 1. The average muscle moment pattern generated about the ankle during one complete stride (shaded area denotes the range of values). The toe-off (TO) and foot-strike (FS) positions kinematically divide the stride into air phase and ground phase. The air phase is kinetically divided into minimal dorsiflexor (TO-A) and minimal plantar flexor (A-FS) dominance. The ground phase consists of plantar flexor dominance throughout (FS-TO). In the production of maximum velocity, the level of plantar flexor activity during touchdown is an important factor.

concentric contraction about the ankle. The strong moment generation during eccentric contraction, with a rapid decrease in moment magnitude once concentric contraction is initiated, points to the efficient utilization of the enhanced strength capabilities of a muscle group working eccentrically, while indicating that the widely held belief of the importance of the plantar flexors in the latter stages of the ground phase has perhaps been overstated.

At the onset of the air phase, the muscle moment about the knee is dominated by the knee extensors (Figure 2). Since the knee action is one of flexion, the extensors are working eccentrically to halt the angular momentum of the leg and foot. Thus, the task of positioning the leg in a flexed position in preparation for the swing-through appears to be one of limiting, not initiating, knee flexion. Once knee flexion has been halted, the knee extensors began working concentrically as the entire limb is rotated anteriorly. As the swing-through progresses, the muscle moment pattern shifts from extensor to flexor dominance interspaced with a period of minimal activity. Initially, the flexors are working eccentrically to limit the amount of knee extension; however, just prior to foot strike the flexors succeed in arresting extension and begin producing flexion through concentric contraction. At foot-strike, the flexor dominance continues briefly in an effort to decrease the horizontal braking ground force. Shortly after ground contact, the knee extensors achieve dominance. This action is essential in terminating the negative vertical velocity of the body (eccentric contraction), then producing both positive vertical and horizontal velocity during the latter stages of the ground phase (concentric contraction). As toe-off is approached, the knee extensors decrease in activity to protect the rapidly extending joint from forceful hyperextension.

From the point of toe-off, the hip flexors (Figure 3) work to stop the posterior rotation of the thigh (eccentric contraction) and generate anterior rotation (concentric contraction). Once this has been accomplished, the muscular contribution is minimized briefly during a period of small angular acceleration, which was termed the "ballistic phase" by Dillman (1971). Following this brief hiatus, the hip extensors are recruited to halt the anterior thigh rotation (eccentric contraction) and then rotate the thigh posteriorly (concentric contraction) as foot-strike is approached. At foot-strike, and briefly into the ground phase, a high extensor impulse is generated. This muscular activity, which has been related to the incidence of hamstring injury, is necessary to minimize the horizontal braking forces produced during this portion of ground contact. As the phase progresses, the muscle dominance shifts to the hip flexors as the trunk is rotated into the impending air phase.

The muscle moment results at the elbow indicate that the primary purpose of the activity is to maintain the forearm in a flexed position. The results of the upper arm indicate that their main purpose is in maintaining body balance during the stride. Neither of the arm joint results indicate that the effort is a contributing factor in the sprint performance.

The Critical Kinetic Patterns

To identify the critical muscle dominance involvement in non-fatigued sprinting, the area under each phase of the muscle moment results (Figures 1, 2, and 3) for each joint was determined for all of the involved sprinters. These results were then correlated (height and weight factored out) with

the most obvious measure of success, average horizontal velocity. Preliminary results indicate that, as expected, success in producing maximum velocity is dependent upon the ability to produce large amounts of muscle moment in the lower limbs. The greatest contributor to sprint success appears to be the muscular activity at the hip (Figure 3). From toe-off to foot-strike, the hip flexor activity needed to recover the leg, as well as the hip extensor effort produced to halt leg recovery and extend the limb toward foot-strike, are significant contributors. The hip extensor moment needed to continue the extension after touchdown is another major contributor. At the knee (Figure 2), the flexor moment prior to foot strike, the continuing flexor activity just after impact, and the extensor moment during the ground phase initially seem to be significant factors. Finally, the level of plantar flexor activity at the ankle (Figure 1) appears to be a significant contributor. Although this research has not progressed sufficiently to make specific conclusions, it is obvious that, as far as sheer velocity is concerned, the ability to produce muscular power in the lower limbs is of paramount importance.

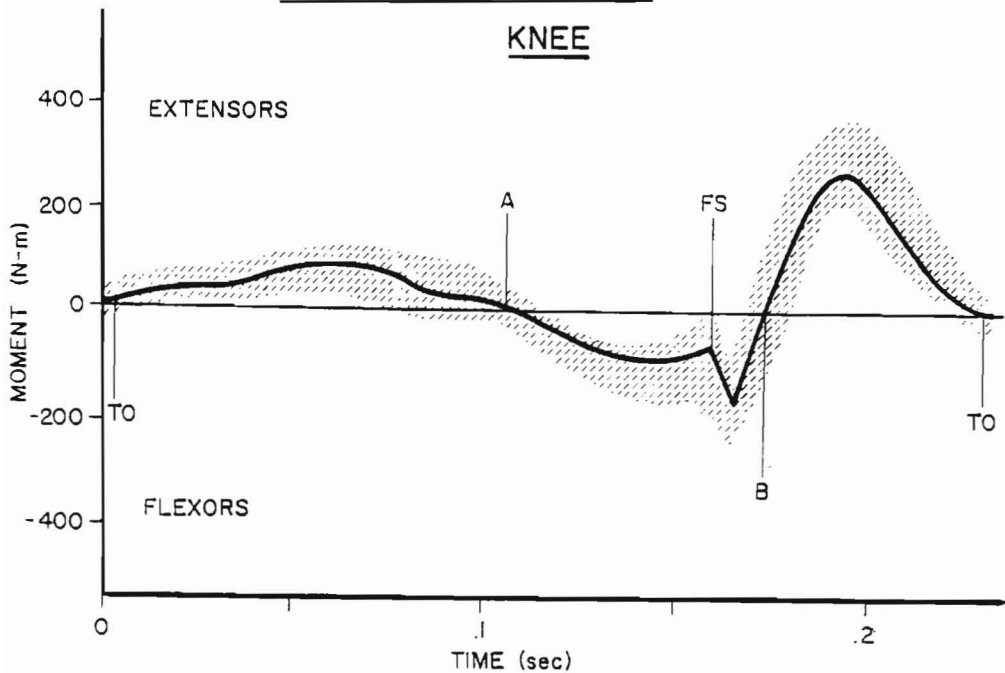


Figure 2. The average muscle moment pattern generated about the knee during one complete sprint stride (shaded area denotes the range of values). The toe-off (TO) and foot-strike (FS) positions kinematically divide the stride into air phase and ground phase. The air phase is kinetically divided into extensor (TO-A) and flexor (A-FS) dominance, with a ballistic period around A. The ground phase is kinetically separated into flexor (FS-B) and extensor (B-TO) dominance. In the production of maximum velocity, the flexor moment prior to foot-strike, the flexor dominance after impact, and the extensor moment during the ground phase are major contributors. In the battle against fatigue, maintenance of the flexor and extensor moments during ground contact are the critical values at this joint.

Although the ability to produce maximum horizontal velocity is important in sprinting, the ability to maintain the generated velocity over the duration of the race is also a critical factor. Research into the alteration in the muscle moment due to fatigue indicates that, as expected, the ability to maintain the level of muscle force as the race progresses is paramount in maintaining velocity. The unexpected discovery was that much of the ability to maintain the level of muscular effort comes from the ability of the better sprinters to produce a more efficient movement pattern. This conclusion was supported by a number of muscle moment increases in certain phases of the poorer sprinter's stride as fatigue developed. This indicates that it is not simply the inability to produce the level of muscle effort, but the inability to produce the muscle force in the most efficient manner that hinders a sprinter as fatigue becomes a factor.

The significant kinetic results that alter sprinting speed during fatigue all occur during the ground phase of the stride. Due to fatigue altered mechanics beginning prior to foot-strike, the poorer sprinter is

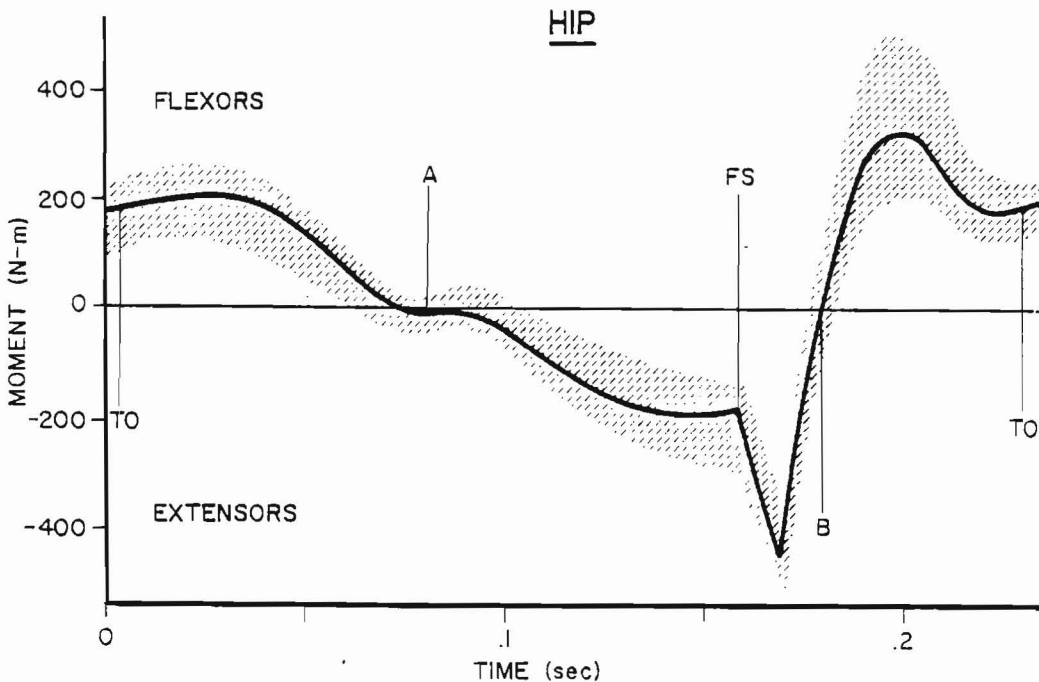


Figure 3. The average muscle moment pattern generated about the hip during one complete sprint stride (shaded area denotes the range of values). The toe-off (TO) and foot-strike (FS) positions kinematically divide the stride into air phase and ground phase. The air phase is kinetically divided into flexor (TO-A) and extensor (A-FS) dominance, with ballistic period around A. The ground phase is kinetically separated into extensor (FS-B) and flexor (B-TO) dominance. In the production of maximum velocity, all of the moments are major contributors. As fatigue sets in, maintenance of both extensor and flexor moments during the ground phase are critical values at this joint.

forced to generate greater muscular activity at both the hip (Figure 3) and knee (Figure 2) during the initial portion of the ground-phase, while the better sprinter maintains both mechanics and level of effort as fatigue sets in. The inefficient mechanics of the fatigued poorer sprinter continue to effect the activity during the latter portion of the ground-phase since productive muscular activity is decreased at both the hip (Figure 3) and knee (Figure 2). Again, since the better sprinter maintains the non-fatigued mechanics to a greater degree, a more efficient muscular action is possible. The ability of the poorer sprinter to produce greater lower limb moments during the ground-phase, and the lack of differences during the air-phase lower limb moment production as well as the upper limb moments in all phases, indicate that the performance difference does not seem to lie in the inability to produce the necessary moments as much as the inability to coordinate the moment production during fatigue.

The Critical Kinematic Results

Whether the goal is to produce maximum horizontal velocity or maintain velocity when fatigued, proper mechanics is a major factor. There are a number of critical kinematic results that can easily be monitored to determine if muscle effort is being properly applied.

Since muscle moment at the hip is of such great importance in maximum horizontal velocity production, it is of little surprise that the kinematic result of upper leg angular velocity is an excellent measure of sprint performance. Figure 4 shows upper leg angular velocity results for seven of the premier U.S. Sprinters (2 men, 5 women). The maximum recovery velocity, directly related to hip flexor moment during this phase, is an indication of the speed and extent of what is termed "knee lift" in sprinting. The velocity at foot-strike (touchdown) indicates how vigorous the leg has been extended into the ground phase (hip extensor moment), while the take-off velocity demonstrates the ability of the performer to continue the critical extension motion during ground contact (hip extensor moment).

The lower leg angular velocity can also be used to indicate efficiency of motion. The velocity at foot-strike affords the best indicator of the job done by the muscle effort produced about the knee during the stride. As shown in Figure 5, the more successful sprinters tend to maximize this velocity value.

As far as the mechanics of sprinting are concerned, results are indicating that the body position at foot-strike is the most critical in producing an efficient motion. Although the muscle effort during the previous ground and air phase dictates how the body is positioned at foot-strike, two kinematic results can be used to determine the efficiency of the motion. If a sufficient stride length is to be produced, the foot must touch down in front of the body. This action also increases the ground time, which allows longer ground force production (see Figure 6). In addition, if the performer is to avoid slowing the body at foot-strike, the foot horizontal velocity should be near zero. As seen in Figure 7, although zero velocity is not possible, this value should be minimized as much as possible.

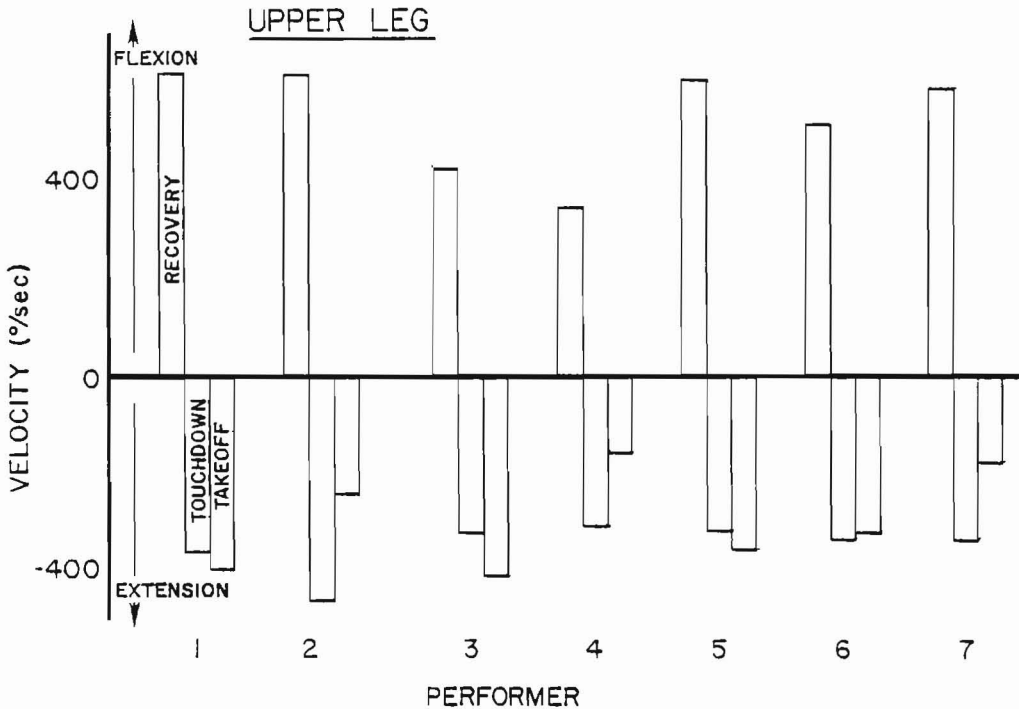


Figure 4. The upper leg angular velocity results for seven world-class sprinters (1-2=male; 3-7=female). The three velocity values; maximum during recovery, at foot-strike (touchdown), and toe-off (takeoff) are all kinematic results that are directly related to the critical kinetic results that determine success in sprinting. The Recovery flexion velocity should be maximized, the Touchdown extension velocity should be maximized, and the Takeoff extension velocity should be equal or greater than the Touchdown result. The Recovery and Touchdown results indicate the quality of the upper leg recovery during the air phase, while the difference between the Touchdown and Takeoff values is indicative of proper mechanics and leg strength during the ground phase.

Although there are numerous kinematic results that can be used to identify the quality of sprinting performance, the results of Figures 4-7 are the most productive. They are interdependent, however, and must be viewed as a whole. Proper upper and lower leg angular velocities will allow a large touchdown distance in front of the body while still producing a low horizontal foot velocity. Improper leg velocities may result in a sufficient touchdown distance, but a poor foot velocity, producing a braking action on the body. Likewise, poor leg action may result in a good foot velocity, but at the expense of a decreased touchdown distance, resulting in a shortened ground time.

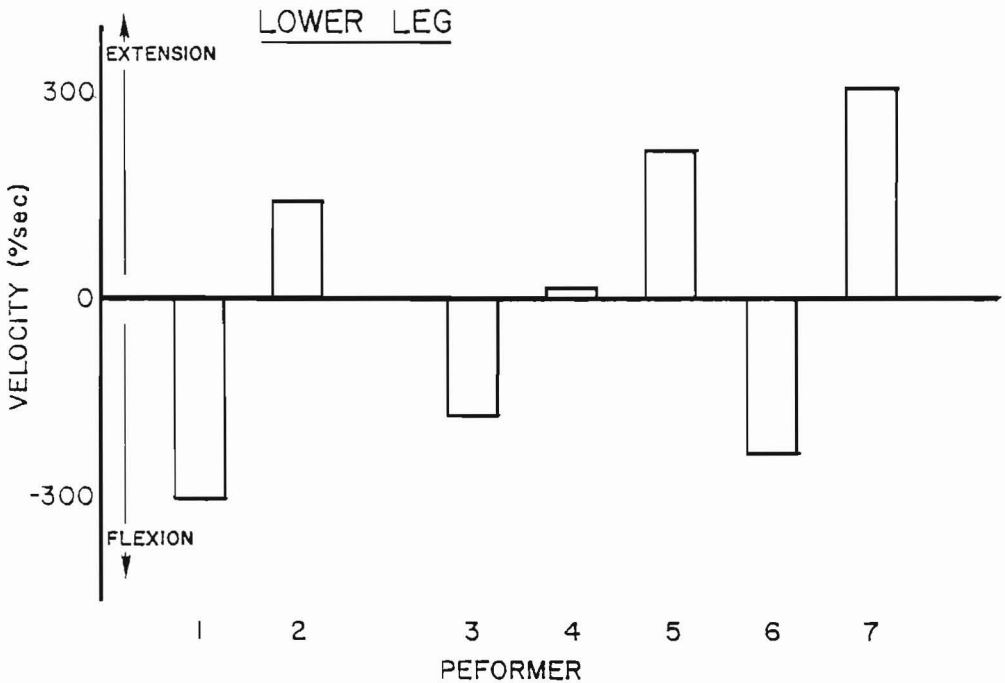


Figure 5. The lower leg angular velocity for seven world-class sprinters (1-2=male; 3-7=female). The velocity value, that of flexion or extension at foot-strike (touchdown), is the best kinematic lower leg result that is directly related to the critical kinetic results that determine success in sprinting. At foot-strike, this value should be maximized, producing as much flexion as possible.

It is evident that, in the kinematic variables that are directly related to the ability to produce muscular force, the most successful performers produce the most favorable results as a whole. In figures 4-7, the superior performance of sprinters one (1) and six (6) support this conclusion. It must also be noted that poor mechanics can be overcome with superior strength and, likewise, poor strength can be compensated by good mechanics. In both cases, however, the resulting performance will be compromised, regardless of the level of achievement.

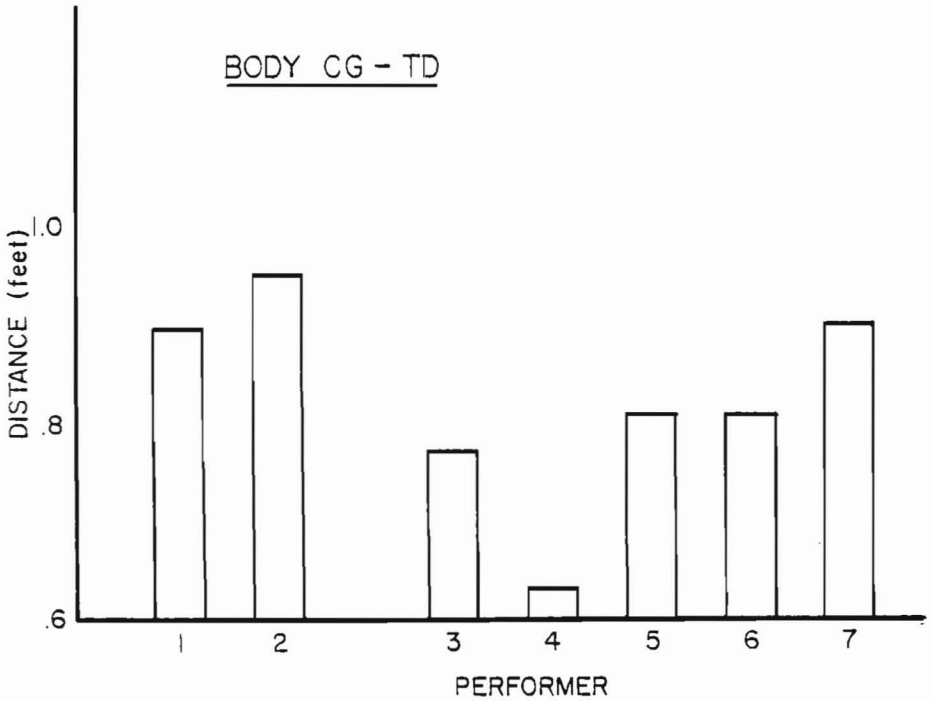


Figure 6. The horizontal distance from the body center of gravity (CG) and the point of foot-strike (touchdown) of seven world class sprinters (1-2= male; 3-7=female). This distance should be maximized to increase stride length and ground time, however, it must be accomplished in the correct manner. Proper upper and lower leg recovery should produce a large body CG to touchdown distance, while also insuring high upper leg extension (Figure 4) and lower leg flexion (Figure 5) at foot-strike.

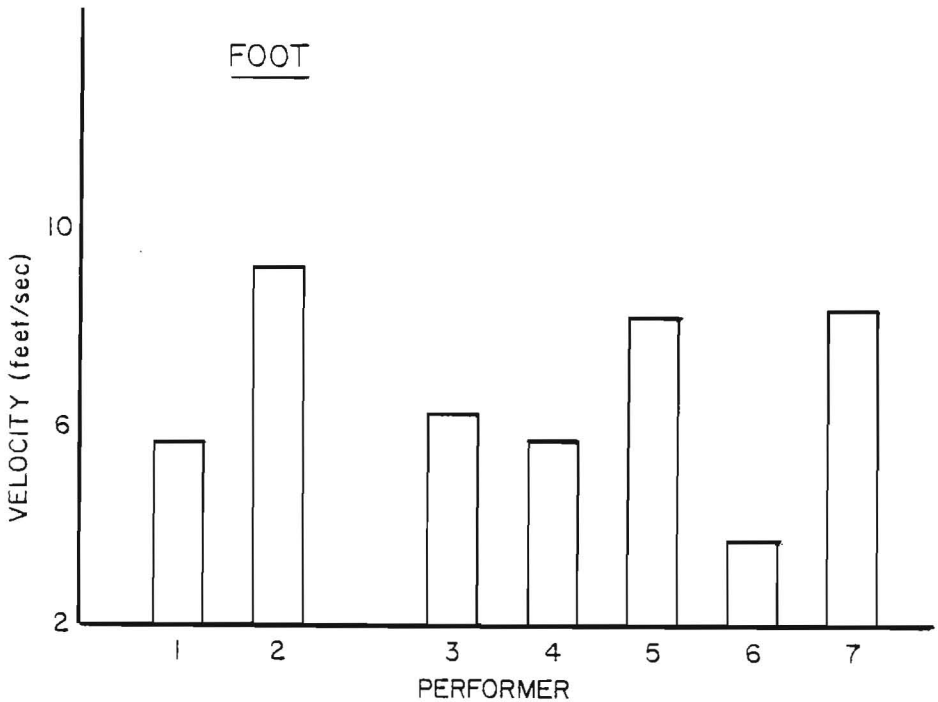


Figure 7. The horizontal foot velocity at foot-strike (touchdown) for seven world class sprinters (1=2=male; 3-7=female). This velocity should be minimized to limit the amount of horizontal braking during the initial portion of touchdown, however, it must be accomplished in the correct manner. Proper upper and lower leg recovery should produce high upper leg extension (Figure 4), high lower leg flexion (Figure 5), a large body CG to touchdown distance (Figure 6), as well as a minimal foot velocity as foot-strike occurs.

Conclusions

The concentrated research effort on the sprint stride has identified the basic kinetic patterns involved in producing the movement. From these results, the critical kinetic patterns that dictate success in producing maximum velocity, as well as maintaining the velocity as fatigue sets in, have begun to be identified. Finally, a number of easily obtainable kinematic results that are directly related to the difficult to obtain kinetic results have been determined. Although much of this research is still in progress, the results have been applied to evaluate the mechanics of world-class sprinters. As the research progresses, the application benefit should increase to an even greater extent.

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