THE TAKEOFF IN THE LONG JUMP AND OTHER RUNNING JUMPS

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Despite its importance to success in the long jump, the takeoff has been accorded little attention by sports biomechanists. We conducted a study to determine the characteristics of an athlete's technique that determine the vertical velocity gained during the takeoff. We found that the vasti, soleus and gastrocnemius experienced a lengthening-shortening sequence of actions during the takeoff and that enhancement due to use of the stretch-shorten cycle did not make a significant contribution to the vertical velocity developed via these muscles. Standing and running vertical jumps from a two-feet takeoff were found to involve different modes of muscle action. Running long and vertical jumps and sprinting involve almost identical modes of muscle action. The results of our study of the long jump appear, therefore, to apply to running jumps in general and to sprint running.

KEY WORDS: biomechanics, long jump, muscle lengths, vertical jump, sprinting

LONG JUMP: Success in the long jump requires (a) a fast approach run; (b) an effective takeoff; and (c) a well-controlled landing. Despite its central importance to success in the event, the takeoff has been accorded little attention by sports biomechanists (Hay, 1985; 1992). Many investigators have presented data on the initial and final conditions of the takeoff -- for example, the coordinates and velocities of the center of gravity, the inclinations of the segments, the angles of the joints and the angular velocities and momenta of the segments, at the instants of touchdown and takeoff -- but very few have made useful contributions to our knowledge of the actions of the athlete during the approximately 120 ms separating these two instants. What an athlete should do during this short interval of time to get the best results is still an open question.

Table 1 lists the U.S. medallists in the men's and women's long jump events at the World Championships and Olympic Games over the ten year period from 1987-1996. Over that period, U.S. men won 71 percent of the medals on offer and U.S. women (actually just one woman, Jackie Joyner-Kersee) won 24 percent.

In the course of our service work with the top U.S. long jumpers, I have been asked frequently by coaches why our women long jumpers have been much less successful than their male counterparts. They live in the same country. They go to the same schools. They appear to have equally good coaches. They compete in the same meets. Why is it that they have so much less success?

To obtain an initial indication of the answer to this question, we conducted an informal pilot study using data we had gathered on top U.S. women jumpers in the course of our service work and data reported in the literature on Olympic finalists (Nixdorf and Brüggemann, 1990). Figure 1 compares selected measures of the performances of seven leading U.S. long jumpers (indicated by the black dots) with the corresponding mean and range of values for the finalists in the 1988 Olympic Games (indicated by the cross-hatched area and the central dashed line crossing it.)

These data showed that the U.S. athletes ...

1. Arrived at the board with horizontal velocities dose to the average for the Olympic finalists.
2. Lost less horizontal velocity during the takeoff than was average for the Olympic finalists.
3. Took off from the board with horizontal velocities above-average; and with vertical velocities and angles of takeoff below average for the Olympic finalists.

Table 1 U.S. Medallists in Men's and Women's Long Jump Events at World Championships and Olympic Games (1986-1996)

Competition	Men's Long Jump	Women's Long Jump
World Championships (Rome, 1987)	1. Lewis 3. Myricks	1. Joyner-Kersee
Olympic Games (Seoul, 1988)	1. Lewis 2. Powell 3. Myricks	1. Joyner-Kersee
World Championships (Tokyo, 1991)	1. Powell 2. Lewis 3. Myricks	1. Joyner-Kersee
Olympic Games (Barcelona, 1992)	1. Lewis 2. Powell 3. Greene	3. Joyner-Kersee
World Championships (Stuttgart, 1993)	1. Powell	
World Championships (Gothenburg, 1995)	3. Powell	
Olympic Games (Atlanta, 1996)	1. Lewis 3. Greene	3. Joyner-Kersee

This analysis suggested that the primary difference between the two groups lay in the inability of the U.S. jumpers to generate vertical velocity at takeoff.
In pursuing this issue, and to improve our understanding of the takeoff in running jumps in general, we next conducted a study to:

Determine those characteristics of an athlete's technique that determine the magnitude of the vertical velocity gained during the takeoff in women's long jumping.

Our study was focussed on four mechanisms thought to develop vertical velocity during the takeoff:
1. A rotating-lever mechanism, which represents the forward and upward rotation of the athlete's body about a transverse axis through her ankle
2. a concentric mechanism, which represents the actions of those extensor muscles of the jumping leg that shorten without prior lengthening;
3. an eccentric-concentric mechanism. which represents the actions of those extensor muscles of the jumping leg that are first stretched'before being allowed to shorten; and
4. a free-limbs mechanism, which represents the upward swinging motions of the arms and free leg.

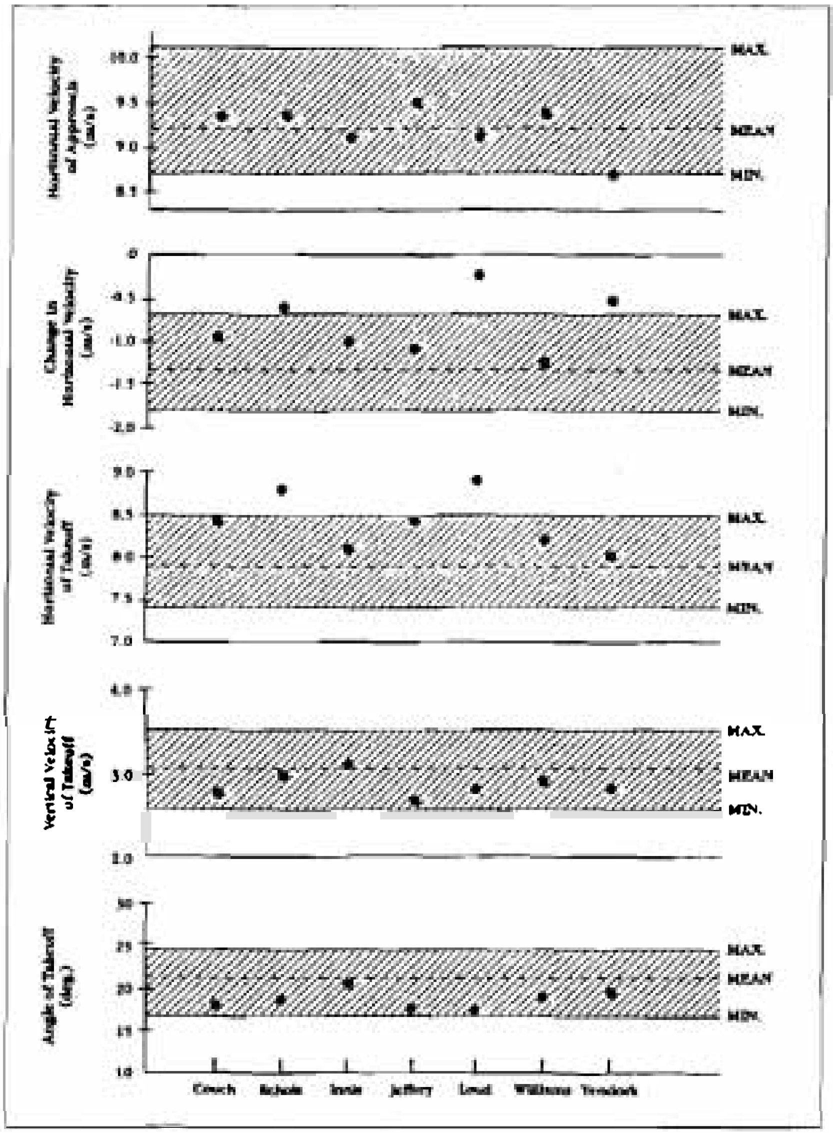

Figure 1 - The horizontal velocity of the center of gravity (CG) at the instant of touchdown at the board (the horizontal velocity of approach), the change in the horizontal velocity of the CG during the takeoff, the horizontal velocity of the CG at takeoff, the vertical velocity of the CG at **takeoff** and the angle of takeoff, for seven elite U.S. female long jumpers. The maximum and minimum values (bounding the cross-hatched areas) and the mean values are based on the best jumps of seven finalists in the women's long jump at the **1988** Olympic Games in Seoul (Nixdorf and Briiggemann, **1990).**

Eleven elite female long jumpers performed six, full-effort jumps from a full-length approach run as in a **competition**. The takeoff was performed from a force platform and each trial was recorded with two, high-speed motion-picture cameras. The trial in which each athlete recorded her best distance; and all the trials by the one subject who had six analysable trials were analysed. Various measures of the four mechanisms were defined and values for these measures determined from digitised coordinate data obtained from the film records. Two statistical analyses were conducted -- one a cross-sectional analysis of the best trials by all eleven subjects; and the other a longitudinal analysis of the six trials by the one subject mentioned earlier. In these analyses, the measures for each mechanism were correlated with the corresponding changes in vertical velocity during the takeoff and the correlations obtained were then tested for significance.

Rotating Lever and Free Limbs Mechanism: The correlations of the measures of the rotating-lever and the free limbs mechanisms with the change in vertical velocity suggested that coaches and athletes concerned with developing greater vertical velocities at takeoff might well consider placing emphasis on ...

1. having the center of gravity of the non-support leg and the arm on the support-leg side low at touchdown and high at takeoff;
2. swinging the non-support leg and the arm on the support-leg side vigorously forward and upward during the takeoff; and
3. having the centre of gravity only a short distance forward of the ankle at takeoff -- an angle of the CG-ankle line with the forward horizontal of 70-75 deg seems desirable.

Concentric and Eccentric-Concentric Mechanisms: A three-dimensional model of the takeoff leg was developed to compute the muscle-tendon lengths of six muscles (or muscle groups) – gluteus maximus, hamstrings, vasti, rectus femoris, soleus and gastrocnemius. The data obtained from digitising the films were used to determine how the lengths of these muscles changed during the takeoff.

Figure 2 shows a set of muscle length data plotted against time for a typical subject. If we assume that these muscles were all active throughout the takeoff -- and electromyographic data in the literature supports that assumption for the most part -- these data show ...

1. that the gluteus maximus remained at a near-constant length for the first part of the takeoff and then shortened;
2. that the hamstrings shortened throughout the takeoff;
3. that the rectus femoris lengthened throughout the takeoff;
4. and that the vasti, soleus and gastrocnemius experienced the lengthening-shortening sequence of actions characteristic of the stretch-shorten cycle.

The forms of the curves were consistent for all subjects, except in the case of the triceps surae muscles, soleus and gastrocnemius. In these cases, there were two variants. Those subjects who landed flat-footed at the end of the last stride of the approach had muscle length vs time curves for the triceps surae muscles that showed a lengthening-shortening sequence of actions. Those who landed heel-first had muscle length vs time curves that showed the muscles shortening initially (as the sole of the foot came down to the ground), then lengthening and then shortening again.

Having established these patterns, we next defined a series of measures derived from the muscle length vs time graphs. For example, in the case of the triceps surae and vasti muscles, we defined a total of eight variables -- four muscle lengths, two changes in lengths and two average velocities. These variables were then correlated with the change in vertical velocity of the center of gravity during the takeoff.

For the cross-sectional analysis of the best trials by the eleven subjects, none of the correlations was significantly greater than zero. For the longitudinal analysis of all the trials by the one subject, the results were much more interesting. In this case, seven of the correlations were significant (Table 2). Of the seven independent variables involved, six were measures of the actions of the vasti, soleus and gastrocnemius -- the muscles found earlier to experience a lengthening-shortening sequence of actions -- and what follows here will be focussed on these three muscles.

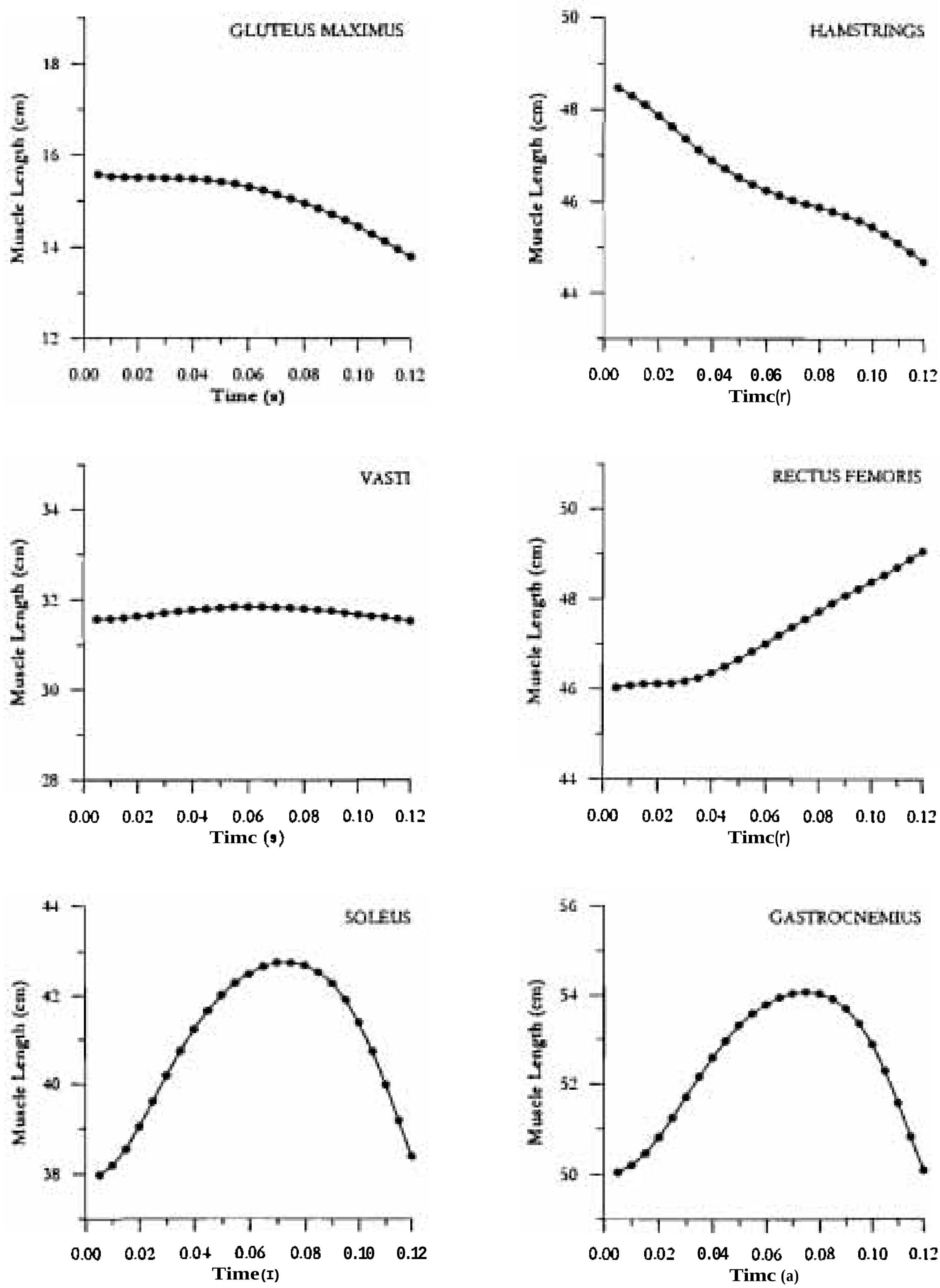

Figure 2 - Example length-time curves for the selected muscles

Table 2 Measures of lengthening-shortening muscle actions significantly related with the change in vertical velocity of the center of gravity of the subject during the takeoff. L = length of muscle, AL = change in muscle length, V = average velocity of muscle length change.

$\Delta\ L_{TAKEOFF}$	Hamstrings
$L_{TOUCHDOWN}$	Soleus
$L_{MINIMUM}$	Soleus
$\Delta\ L_{STRETCH}$	Vasti
	Soleus
	Gastrocnemius
$V_{STRETCH}$	Soleus

These findings indicated ...

1. that the longer the distance over which the vasti, **soleus** and gastrocnemius were stretched, the larger was the gain in vertical velocity

and ...

2. that having the **soleus** short at touchdown and then stretching it rapidly over a long distance was consistent with generating large vertical velocities during the takeoff.

The obvious way in which the stretch lengths and velocities of the triceps surae muscles might have a causal relationship with the gain in vertical velocity is through use of the stretch-shorten cycle. If the enhancement due to the use of this mechanism increased with stretch length and stretch velocity, it would be reasonable to expect that the vertical forces exerted against the ground as the ankle was plantar-flexed would also increase and that this increase in vertical forces would lead to an increased gain in vertical velocity.

There is at least one major obstacle to this line of argument. The concentric action of the triceps surae muscles began **very** late in the support phase of the takeoff. In the longitudinal analysis, for example, the maximum lengths of the muscles -- signalling the start of the concentric phase -- were recorded, on average, after about 75 percent of the duration of the takeoff had elapsed. This means that variations in enhancement due to variations in stretch length and stretch velocity could only have had an effect on the change in vertical velocity during the final 25 percent of the takeoff.

The vertical ground reaction force vs time curve for the best trial by the subject of the longitudinal analysis is shown in Figure 3. This typical curve shows that the change in vertical velocity during the shortening of the triceps surae was relatively small. Further statistical analysis showed that, for each of these muscles, the longer the distance over which the muscle was stretched, the larger was the gain in vertical velocity during the time it was being stretched. There was no suggestion of a relationship between the distance over which a muscle was stretched and the gain in vertical velocity during the subsequent shortening phase.

In total, the significant results for the vasti and the triceps surae muscles suggest

1. that the shorter these muscles were at **touchdown**, the longer was the distance over which they were subsequently stretched;

2. the longer the distance over which they were stretched, the faster they were stretched;
3. the faster they were stretched, the larger the forces they generated (force-velocity relationship);
4. the larger the forces they generated, the larger was the vertical velocity developed,
5. and, finally, that enhancement due to use of the stretch-shorten cycle did not make a significant contribution to the development of vertical velocity via these muscles.

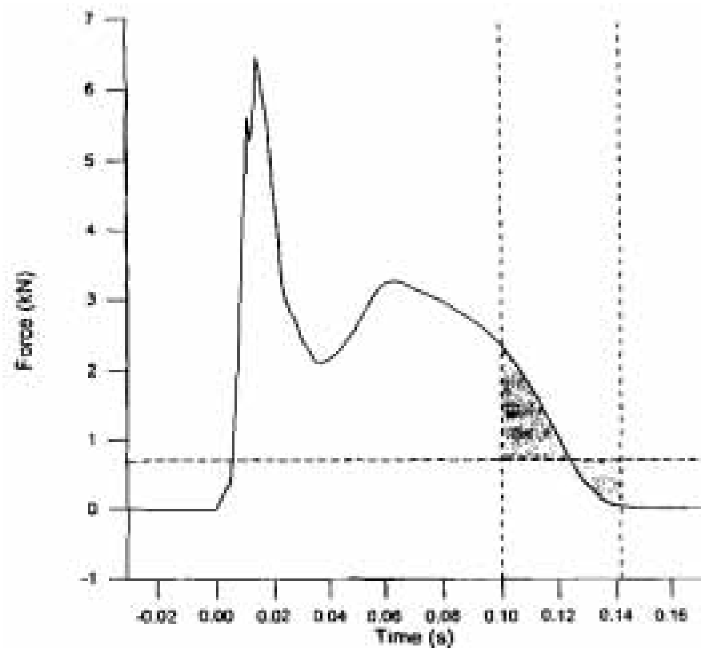

Figure 3 - The vertical ground reaction force vs time curve for a typical subject. The horizontal line represents the weight of the subject and the two vertical lines indicate (a) the time at which the maximum lengths of the triceps surae muscles were recorded and (b) the time of takeoff. The upper shaded area represents the gain in vertical velocity obtained during the initial concentric action of the triceps muscles. The lower shaded area represents the loss in vertical velocity during the final concentric action of the same muscles. The vector sum of this gain and loss in vertical velocity is equal to the change in vertical velocity during the concentric action of the muscles.

OTHER RUNNING JUMPS: Since completing this work, we have begun exploring the corresponding muscle actions in other forms of jumping (both standing and running) and in sprinting, with a view to establishing whether our findings are representative of jumping and jump-like motions in general.

Vertical Jump: Grosvenor analysed vertical jumps from an initial standing position and following approach runs of one, three, five and seven steps. These jumps were performed with a takeoff from two feet to reach with both hands towards a volleyball suspended directly above a marked takeoff area. Although this skill is rarely performed with approach runs of more than three steps, the jumps performed here were otherwise similar to those performed in the execution of a volleyball block.
One experienced, male, volleyball player served as the subject and performed three trials under each of the five conditions. His performances were recorded in side view using a motion-picture camera. For each of the conditions, the trial in which the highest vertical velocity of the centre of gravity at takeoff was recorded was analysed. Although Grosvenor's study was not concerned with muscle action, her digitised coordinate data were

subsequently used to compute muscle-tendon length changes during the takeoff for the same six muscles (and using the same computational procedures) as used in our long jump study. And here is what we found ...

Standing Vertical Jump: Although there was some variation among muscles early in the takeoff, five of the six muscles had a lengthening-shortening sequence of actions immediately prior to the instant of takeoff. The rectus femoris was the sole exception.

Running Vertical Jump: With two exceptions in a total of **24** combinations of ***6*** muscles and **4** lengths of approach, the muscle actions observed were the same as we found for the running long jump. That is, the gluteus maximus and hamstrings shortened; the rectus femoris lengthened; the vasti lengthened and then shortened; and the soleus and gastrocnemius shortened, lengthened and then shortened again. This last sequence was the same as that recorded in the running long jump for those subjects who landed heel-first at the end of the last step of the approach and was exactly as expected, given that the subject here landed on his heels at the end of the last step of his running vertical jumps.

And so, in summary ...

(a) Standing vertical jumps and running vertical jumps performed from a two-feet takeoff were found to involve different modes of muscle action. For the standing vertical jump, a lengthening-shortening sequence of muscle actions was evident in the final part of the takeoff for five of the six muscles analysed. The existence of this characteristic sequence of actions means it is possible that use of the stretch-shorten cycle led to an enhanced contribution of muscles crossing the hip, knee and ankle joints to the generation of vertical velocity at the instant of takeoff. For the running vertical jump, the same sequence was seen only in the records for the vasti and triceps surae muscles. The use of the stretch-shorten cycle in this case may also have led to an enhanced contribution of these muscles to me generation of vertical velocity at the instant of takeoff. Alternatively, it maybe that, as in the case of the running long jump, the vertical forces exerted as the muscles shortened were too small and/or were exerted too late in the takeoff to have a significant effect on the outcome (that is, on the vertical velocity of the athlete at the instant of takeoff).

(b) A running long jump and a running vertical jump involve almost identical modes of action of the major extensor muscles of the takeoff leg (or legs). This suggests that the results obtained in our study of the running long jump may apply to running jumps in general and not only to long jumps performed by elite female long jumpers.

Sprinting: Simonsen et al (1985) used cinematography to determine the lengths of the muscle-tendon units, and telemetered electromyography to determine the electrical activity. of nine muscles of the right leg over one complete cycle of sprinting action. Their subjects were two male sprinters with best 100 m times of 10.7 and 11.1 s.
The data for one of the subjects running "at maximum speed" 30-60 m from the start are shown in Figure **4.** These data were gathered, three muscles at a time, during three separate trials. They show that during the support phase of the right leg ...

1. the gluteus maximus and the hamstrings shortened throughout -- the latter finding has been confirmed recently in a study of strains and strain rates in the hamstrings during sprinting (Don, 1998);
2. the vasti lengthened and then shortened;
3. the rectus femoris lengthened throughout; and
4. the soleus lengthened and then shortened.

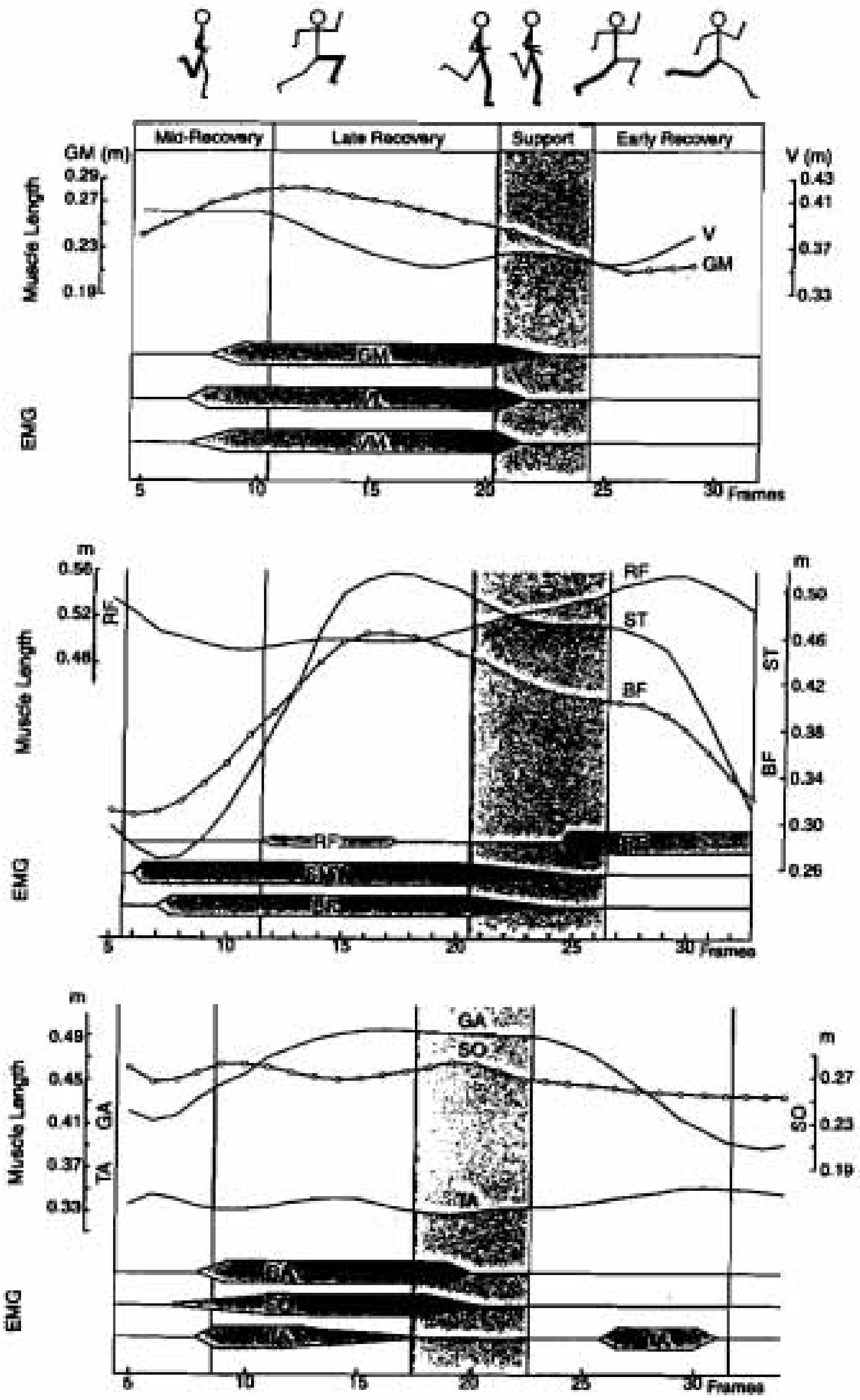

Figure 4 - Muscle length and electromyographic activity **vs** time (in no. of frames) for one running cycle of the right leg (thickened in the stick figures at the top). GM = **gluteus maximus;** VL = **vastus** lateralis; VM = **vastus** medialis; VA = VL and VM combined; RF = rectus femoris; SM = semimembranosus; ST = semitendinosus; SMT = SM and ST combined; GA = gastrocnemius; SO = **soleus;** and TA = tibialis anterior. (Adapted with permission from Simonsen et **al,** 1985).

With one exception, all of these modes of action were identical to those we found for the long jump and the volleyball block. The sole exception was the gastrocnemius which remained at a near-constant length throughout the support phase.

Thus, although the actions differ with respect to the manner of landing -- long jump heel-first or foot flat; volleyball block heels-first; and sprinting ball of foot first -- the associated muscle-tendon unit length changes during the support phases are very similar.

These findings suggest that, although sprinting is not normally considered a jumping skill, the muscle actions during support have much in common with those observed in jumping. (It is perhaps worth noting here that it is very difficult to generate an acceptable definition of jumping that excludes a step in sprinting.)

DISCUSSION: The various findings of these studies raise some further issues that seem worthy of consideration.

Cross-sectional vs Longitudinal Analyses?: The original design of our long jump study was a cross-sectional one. It was only the happy finding of a subject who had six trials in which her takeoff foot was squarely on the top plate of the force platform that permitted the conduct of a longitudinal analysis of her jumps.

The results obtained in a cross-sectional analysis based on the best trials of a group of elite female long jumpers can be generalised to other groups of elite female long jumpers. We can say, for example, that the change in vertical velocity experienced by a group of elite female long jumpers is related to beta, the inclination of the CG-to-ankle line at the instant of takeoff because we have found a significant positive relationship between these two variables that supports this conclusion. The results cannot be generalised to a given individual, however. We cannot say that a given athlete would generate a greater change in her vertical velocity if she increased the magnitude of beta.

The reverse is true for a longitudinal analysis. The results obtained in a longitudinal analysis of a set of trials by a given subject can be generalised to the population of trials performed under similar circumstances by that same subject. We can say, for example, that this subject would generate a greater change in her vertical velocity if she increased the maximum vertical velocity of her free (or non-support) leg during the takeoff. We have found a significant positive relationship between this variable and the change in vertical velocity that supports this conclusion. The results cannot be generalised to other athletes. We cannot say that another athlete would generate a greater change in her vertical velocity if she were to make a similar change in the action of her free leg.

These elementary notions of generalisation suggest that a cross-sectional analysis is best suited for research in which the aim is to characterise the techniques generally used when performing a given motor skill and that a longitudinal analysis is best suited for service work in which the aim is to improve the technique of a given athlete. There is, however, another possibility -- the possibility that the most powerful approach is one in which both designs are used simultaneously. To my knowledge, no-one has yet developed a systematic procedure that incorporates this approach for either research or service purposes.

Finally, the difference in the number of significant relationships obtained in our two analyses probably stemmed from the different roles played by the physical attributes of the subjects in the two cases. In the cross-sectional analysis, the change in vertical velocity during the takeoff was certainly influenced by the techniques employed by the subjects and it was probably influenced also by their physical attributes -- their heights, weights, speeds, strengths etc. In the longitudinal analysis, the subject's physical attributes were presumably unchanged over the duration of the "competition" and any differences in the changes in vertical velocity were primarily due to changes in technique. It is thus much easier for a technique variable to be found significant in a longitudinal analysis than in a cross-sectional one where the relationship must be sufficiently strong that it transcends the confounding influences of the variables characterising the physical attributes of the subjects.

Practical Applications: Given that research on muscle-tendon unit length changes during the performance of athletic movements is sparse indeed, it is clearly premature to project the practical consequences or benefits of such research. One can only examine some of the possibilities.

McLean (1990) has determined muscle-tendon unit lengths during cycling and discussed the effects of variations in seat height on the muscle length changes, joint moment arms and muscle EMG activity. He has suggested that variations in seat height move the operating muscles into ranges of motion that are more or less favourable in terms of the force-length relationship and has used measures of muscle length routinely to determine whether the optimum seat height is being used.

The motions of the legs in cycling are severely constrained by the geometry of the bike, the attachment of the feet to the pedals and the lengths of the leg segments of the rider. These constraints make it much easier to modify muscle-length patterns systematically -- as, for example, by altering seat height -- than is the case in jumping where there are many less constraints. Nonetheless, the notion that we may one day be able to use measures of muscle performance as a basis for decisions about technique in jumping is an intriguing and attractive one.

The use of plyometric exercises in the training of athletes in explosive sports and events has increased dramatically over the last few decades. This development has no doubt been due primarily to research showing the performance benefits of the SSC in selected motor skills and, in particular, to various forms of vertical jumping. If further work supports the initial indications (a) that the SSC does not play a significant role in the development of vertical velocity during the takeoff to a running long jump (and perhaps also during the takeoff to running jumps in general) and (b) that the characteristics of the stretching of the triceps surae muscles do have an important role in this respect, such findings may have important practical consequences. It may come to be recognised, for example, that plyometric exercises are beneficial training exercises not because they increase the enhancement obtained from the use of SSCs but because they develop an athlete's ability to benefit from the stretching that precedes the shortening phase of an SSC. Or, to put this in a different way, it may be recognised that coaches and athletes have been doing the right thing (that is, using plyometric exercises) for the wrong reason. It may be, then, that the current emphasis on plyometric training shifts to, or is shared with, training in which the emphasis is on the stretching phase of a movement alone and not on the entire SSC and that exercises like drop or depth jumps (in which athletes step or jump down from a platform, land and then immediately jump upward) are replaced by exercises limited to the first two parts of this three-part sequence -- that is, to the initial drop and landing. But this is, of course, mere speculation. What must be established first is whether the initial indications are supported by further research.

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