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Changes in Muscle Activity Patterns and Kinetics With Increasing Running Speed

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ABSTRACT

Knowledge of muscle actions is essential for understanding biomechanics in running. In this study, 17 young runners were investigated at 13 different running speeds. Telemetric surface electromyograms from lower leg muscles were recorded continuously, and they were synchronized with the recordings of 3-dimensional ground reaction forces from a 10-m-long force platform. As expected, the rate of force production and the peak forces increased with increasing running speed. In the lateral forces, there was a short-duration inward force at the beginning of the contact followed by a longer-lasting outward force. The results revealed further the importance of preactivity and eccentric activity of the leg extensor muscles and the role of the hamstring muscles. The preactivity appears to be a preparatory requirement both for the enhancement of electromyographic activity during the braking phase and for timing of muscular action with respect to the ground contact. The increased force production with increased running speed is, furthermore, partly due to high and long-lasting activity of the hip extensor muscles during the contact phase.

Key Words: electromyography, joints muscle, ground reaction force

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Introduction

Knowledge of muscle activity patterns is essential for understanding biomechanics of running. Joint movements, for example, are the functional results of many active single-joint or multijoint agonist, synergist, and antagonist muscles. In running, the muscle activity patterns in relation to joint motion should be examined primarily with respect to their function during the ground contact. This contact phase represents, for the leg extensor muscles, stretch-shortening cycle action, which is beneficial for the force output (2, 18).

Stride rate and stride length determine running velocity. Their increases seem to be linear between speeds from 3–7 $m \cdot s^{-1}$ (3, 16). Simultaneously, vertical and horizontal peak ground reaction forces (GRFs) increase, but only small changes take place in mediolateral forces with increasing speed (23). The movements of the body segments determine GRFs and their directions. Therefore, the roles of muscle actions are important determinants of running mechanics.

Only one phase of activity has been reported for the gluteus maximus (GM) during the running cycle (17, 22). Its activation begins in late swing when the GM is acting eccentrically to decelerate the thigh. At foot strike, it may also stabilize the thigh and pelvis when extending the hip throughout the early stance phase (3).

The hamstring muscles are not active during early swing, but in the late swing phase they decelerate hip flexion followed by controlling knee extension. When the thigh begins its motion backward before ground contact, the hamstrings act concentrically to extend the hip and flex the knee (3).

The activity of the quadriceps muscle begins just before the foot strike. Its highest activity has, however, been observed during early stance phase when it acts eccentrically (22), whereas in the late stance phase it is not active (1). This phenomenon has been referred to as the paradox situation ''in which the quadriceps activity has usually ceased prior to the beginning of knee extension'' (3).

The plantar flexors, gastrocnemius (GA), and soleus have been reported to be active in the late swing and in the beginning of the stance phase (17). During the ground contact, GA has been shown to contract isometrically, whereas soleus contracts first eccentrically and then concentrically (24). Their antagonist muscle, tibialis anterior (TA), acts eccentrically in the late swing phase and concentrically at touchdown (6, 24).

In general, the extensor muscles of the hip joint have been shown to be the primary movers by accelerating the center of the gravity of the whole body during the ground contact in running (24). Further-

Table 1. Physical characteristics and training history of the runners.

	Female (n = 8)	Male (n = 9)	All (n = 17)
Age (yr)	21 ± 3	20 ± 2	21 ± 2
Height (m)	1.68 ± 0.02	1.80 ± 0.03	1.74 ± 0.07
Body mass (kg)	55.7 ± 4.5	68.1 ± 1.9	62.3 ± 7.2
Fat (%)	18.3 ± 3.0	8.9 ± 1.1	13.3 ± 5.3
Training (yr)	8 ± 3	6 ± 2	7 ± 3
in 1996 (km)	3650 ± 1700	3850 ± 1150	3750 ± 1400
in 1995 (km)	3600 ± 1350	3300 ± 1550	3450 ± 1450

more, the biarticular muscles perform eccentric work during the flight phase and concentric work during the whole ground phase. Monoarticular muscles, however, act first eccentrically and then concentrically during the ground contact. When the running speed increases, Nilsson et al. (22) found that muscles tended to become active earlier with increased activity bursts. However, more detailed information is needed to understand interactions between muscle actions and running mechanics with increasing running speed.

The purpose of the present study was, therefore, to investigate changes in muscle activity patterns of leg muscles and running kinetics at different running speeds on the track.

Materials and Methods

Subjects

Eight women and 9 men middle-distance runners (mean ± *SD*: age, 21 ± 2 years; height, 1.74 ± 0.07 m; body mass, 62.3 ± 7.2 kg) volunteered as subjects for the present study (Table 1). They had a training background of 7 ± 3 years and of 3,800 ± 1,300 km during the year preceding the study. The runners were fully informed of the procedures and possible risks of the experiment. All signed their written consent agreement.

Procedure and Measurements

The subjects were asked to run on a 200-m indoor track for 3 minutes at 5 predetermined submaximal constant speeds of 3.25, 4.00, 4.75, 5.25, and 5.75 $m \cdot s^{-1}$, with a 1-minute recovery period between each test. After 10 minutes of recovery, they ran for a 1-minute period at 4 predetermined constant speeds of 6.00, 6.25, 6.75, and 7.00 $m \cdot s^{-1}$, with a 3-minute recovery between each test. Finally, after a 15-minute serial recovery period, the subjects ran 30 m 4 times (flying 30 m) with increasing running speed so that the last sprint was the individual maximum.

During submaximal running, the subjects ran on the right side of an electrical car, which was paced by its driver. The driver drove counterclockwise around

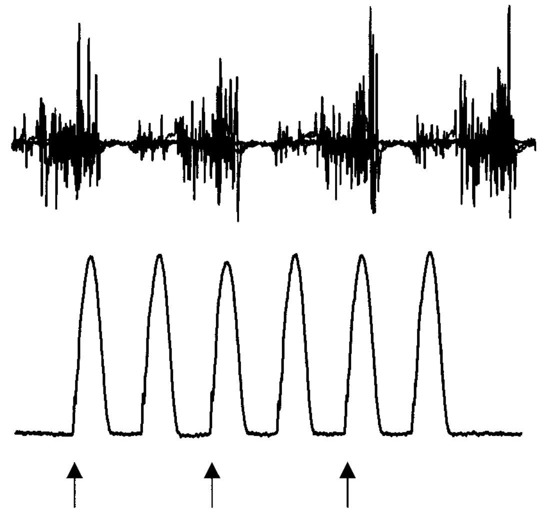

Figure 1. An example of the electromyographic and vertical ground reaction force signals at the running speed of 5 $m \cdot s^{-1}$. The arrow indicates the trigger point for the analysis.

the 200-m-long track at the predetermined constant speed by following the pointer of a speedometer, which was connected to an electromagnetic pulsimeter. During every lap, 3-dimensional GRFs were measured by a 10-m-long force platform (TR-testi, Finland and Kistler, Switzerland: natural frequency ≥150 Hz, linearity ≥1%, crosstalk ≤2%).

Electromyographic (EMG) activity was recorded telemetrically (Glonner, Germany) with surface electrodes (pregelled electrodes, AG/AGCL, Niko, Denmark) from the GM, vastus lateralis (VL), biceps femoris (BF), GA, and TA muscles. The electrodes with interelectrode distance of 38 mm were placed longitudinally over the muscle bellies between the center of the innervation zone and the distal tendon of each muscle. Because of the large distance between the EMG electrode pairs, the crosstalk between muscles was assumed to have minimal influence on the recorded signals (25). The EMG signal amplification was 200 (Glonner Biomes 2000; bandwidth 3–360 Hz per 3 dB^{-1}), and it was digitized simultaneously with the force records at a sampling frequency of 1 kHz.

Analysis

Two–10 contacts at each speed were selected per subject for further analysis. The GRFs and EMGs were divided into braking and push-off phases according to the orientation of the horizontal force (19). The EMG activities were full-wave rectified, time normalized, and integrated in 4 phases: preactivation from 100–50 ms before the contact and preactivation from 50 ms to the beginning of the contact, braking phase, and push-off phase. The vertical force signal was used to identify the beginning and end of the contact (Figure 1). It was also used to calculate step frequency and length.

All recorded signals were also averaged intraindividually at each running speed for obtaining muscle activity patterns and 3-dimensional GRF curves. For further description of running strategy at several speeds, interindividual grand mean curves were drawn as well.

Statistics

Multivariate analysis of variance for repeated measurements was used to test the main effects of repetitions, experimental conditions, and sexes and all combined effects on selected variables. It revealed that the repetition had no statistically significant influence on any main variables. Therefore, all signals of each contact were averaged for the subject at each running speed. Mean and *SD* were calculated by conditions and sexes, from which the latter differed significantly from each other only in GRF variables, which included the body weight. Thus, in the present study, any comparison between the sexes was not performed. The stepwise regression analysis was used to test the importance of the measured parameters for the running speed. The level of significance was $p \leq 0.05$ for all tests.

Results

As expected, the contact times shortened gradually with increasing speed (0.227 ± 0.011 seconds at the slowest speed to 0.115 ± 0.007 seconds at the maximal speed; $p < 0.001$) and its braking (0.110 ± 0.007–0.054 ± 0.005 seconds; $p < 0.001$) and push-off (0.117 ± 0.09–0.062 ± 0.004; $p < 0.001$) phases. The increases in the step frequency (2.79 ± 0.08–4.09 ± 0.19 Hz; $p < 0.001$) and the lengthening in the step length (1.17 ± 0.06–2.03 ± 0.17 m; $p < 0.001$) were again as expected (Figure 2).

Figure 3 demonstrates changes in the GRFs with increasing speed. In the vertical and horizontal directions, the rate of force production and the peak forces increased with increasing speed. In the lateral forces, it was interesting to see the fast inward force of short duration in the beginning of the contact followed by a longer-lasting outward force. The maximal values of lateral forces varied from 30–80 N inward and from 20–60 N outward. The maximal force values increased gradually from 1,665 ± 219–2,134 ± 226 N ($p < 0.001$) in the vertical direction and from 235 ± 42–675 ± 173 N ($p < 0.001$) in the horizontal direction.

The stepwise regression analysis revealed that the averaged horizontal force in the push-off phase was the main factor (88.2%) from the 3-dimensional force parameters to explain the running speed, whereas the same parameter in the braking phase had much smaller explanatory role (10.6%). However, the net resultant force × (body weight)$^{-1}$ and its direction determined primarily the final running speed. Figure 4 demonstrates that the runners had smaller resultant push-off forces with more inclined force direction in respect to

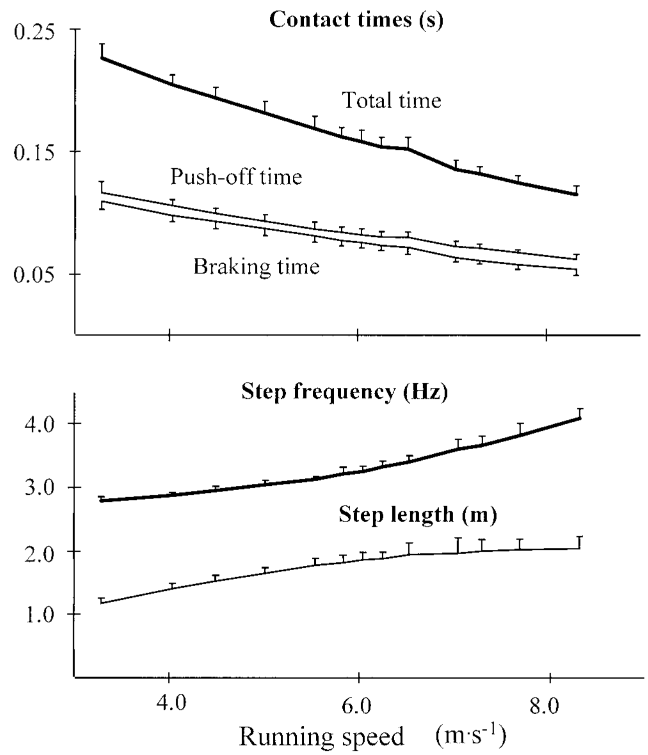

Figure 2. Mean (±*SD*) total contact, braking, and push-off times and mean (±*SD*) step frequency and step length with increased running speed.

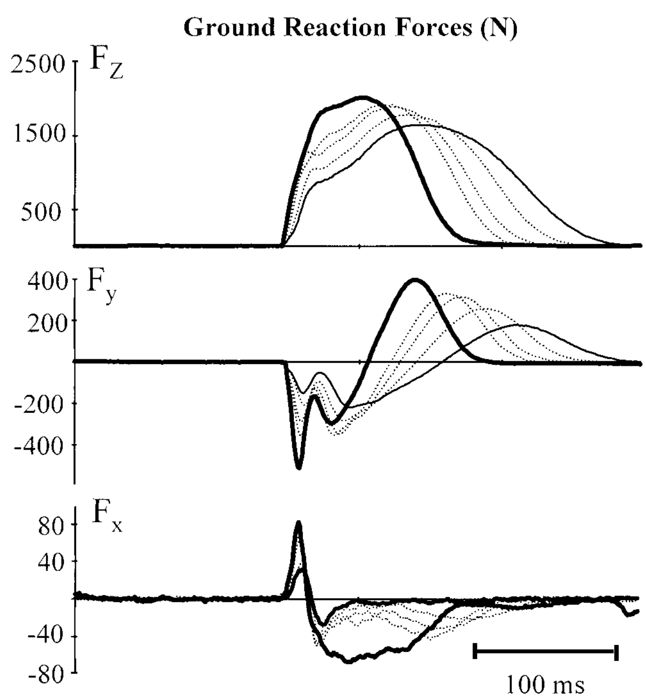

Figure 3. Mean curves of vertical (F_z), horizontal (F_y), and mediolateral (F_x) ground reaction forces from the slowest speed of 3.25 m·s^{-1} (thin solid line) (mean of 170 contacts) up to the maximal speed (thick solid line) (mean of 34 contacts). The dashed lines indicate the respective ground reaction force curves at the 3 medium running speeds (4.75, 6.00, and 7.00 m·s^{-1}).

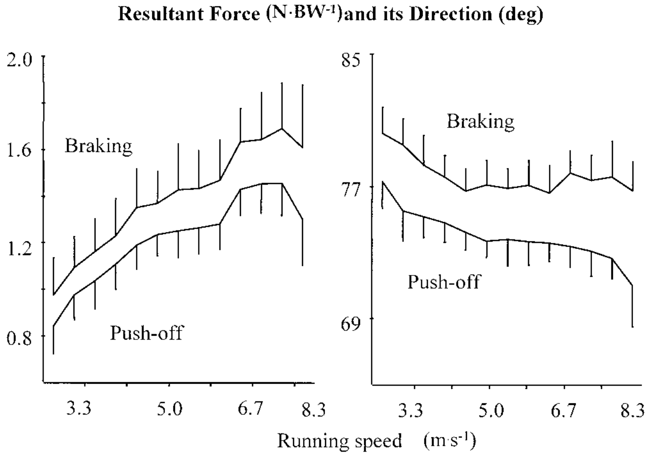

Figure 4. Mean (±*SD*) curves of the average resultant force (F = 48.32–52.38; $p < 0.001$) and its direction (F = 24.70–28.99 $p < 0.01$) with increased running speed.

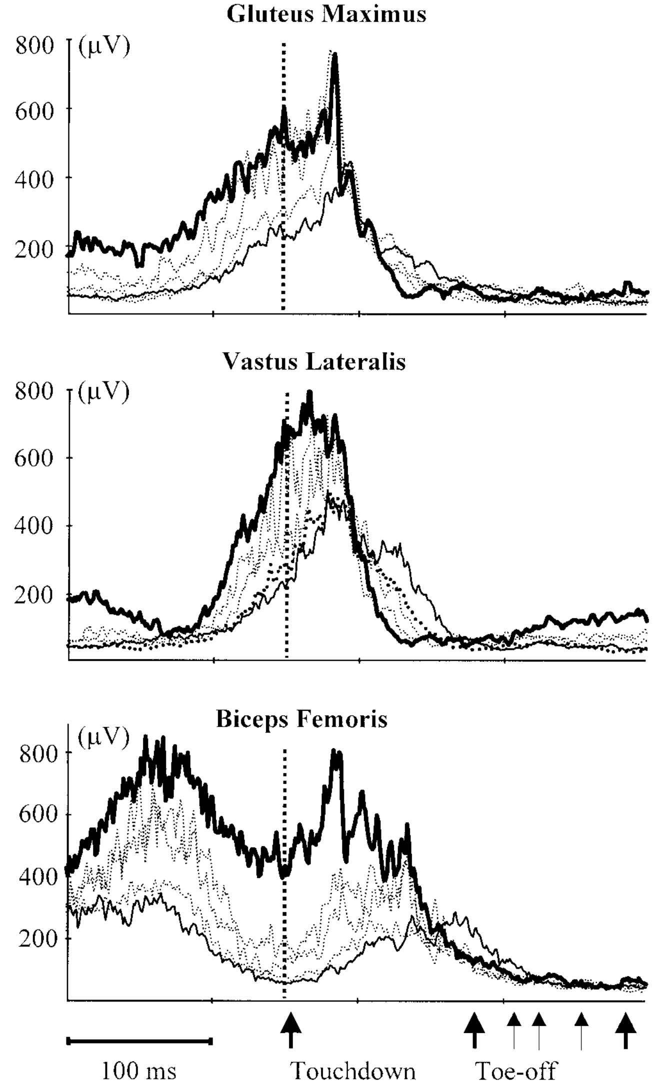

Figure 5. Muscle activity patterns of the gluteus maximus, vastus lateralis, and biceps femoris muscles from the slowest speed of 3.25 m·s^{-1} (thin line) up to the maximal speed (thick line). The dashed lines indicate the respective electromyographic curves at the 3 medium running speeds.

the horizontal line compared with the respective parameters in the braking phase.

One should expect that the changes in the presented mechanical parameters are caused by muscle actions. Therefore, analysis of muscle activity patterns was performed. The GM muscle was active in the late swing and in the braking phase of the contact (Figure 5). Its amplitude increased ($p < 0.05$) with increasing running speed, but the duration of its activity remained constant despite the shortened contact times. In the VL muscle, similar increases in the EMG amplitudes with increased speed were observed ($p <$ 0.001–0.05) (Figures 5 and 6). Its activity, however, almost disappeared early before the toe-off at every running speed.

The greatest changes in the muscle activity pattern were observed in the BF muscle (Figures 5 and 6). This 2-joint muscle seems to be active during the maximal running: its amplitude increased ($p < 0.05$) both in the swinging and contact phases with increasing running speed.

Figure 7 demonstrates that the plantar flexors have an important role in running. As an extensor muscle, GA behaved like the GM and VL muscles. Its activity increased in the prephase and braking phase ($p <$ 0.05). The TA muscle, on the other hand, increased its activity in the middle of the swing phase and slightly in the beginning of the contact ($p <$ 0.01–0.05).

Discussion

The results of the present study emphasize the importance of preactivity and eccentric activity of the leg extensor muscles and the functional role of the hamstring muscles. The increased force production with increased running speed seems to be partly due to simultaneously increased and long-lasting activity of hip extensor muscles. During the stance phase, their action may increase positive work and power around the hip joint, which were transferred through knee and ankle joints to the ground. This can be seen as a kinetic chain of diminished muscle activities starting from the gluteus, through the vasti muscles, finally, to the plantar flexors.

For tolerating higher-impact loads with increasing running speed, the hip and knee extensors and plantar flexors need higher muscular activity. In particular, the GA muscle has been demonstrated to increase its preactivity linearly with increasing running speed (14). The high prelanding and braking activity of leg extensor muscles might prevent unnecessary yielding of the runner during the braking phase. Therefore, preactivation appears to be a preparatory requirement both for the enhancement of EMG activity during the

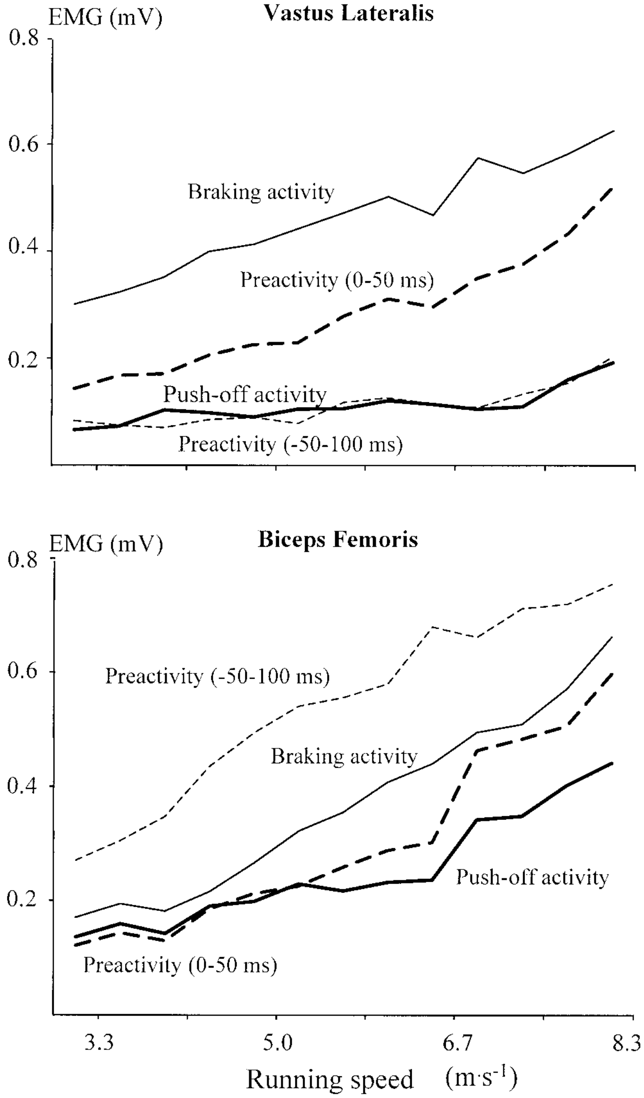

Figure 6. Averaged electromyograms increased ($p <$ 0.001–0.05) both during the preactivity (0–50 milliseconds before the contact) and the braking phases in the vastus lateralis muscle, whereas the biceps femoris muscle increased its activity ($p <$ 0.001–0.05) in every phase.

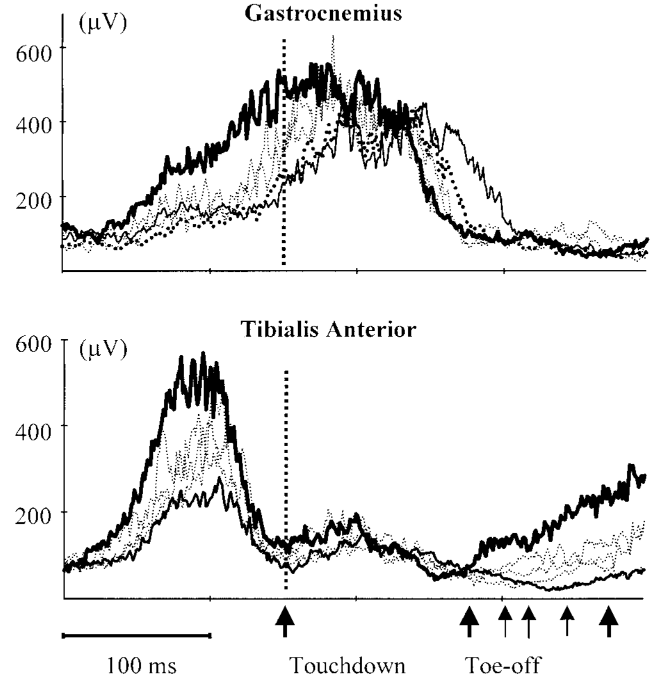

Figure 7. Muscle activity patterns of the gastrocnemius and tibialis anterior muscles from the slowest speed of 3.25 $m{\cdot}s^{-1}$ (thin line) up to the maximal speed (thick line). The dashed lines indicate the respective electromyographic curves at the 3 medium running speeds.

braking phase and for timing of muscular action with respect to the ground contact. Centrally programmed prelanding activity (10) seems to be important for regulating the landing stiffness (7) and for compensating local muscular failure (12). Furthermore, preactivity is assumed to increase sensitivity of the muscle spindle via enhanced α-γ-coactivation potentiating stretch reflexes (9), enhancing tendomuscular stiffness (11, 21), and, therefore, increasing economy of running (15).

The increased stride frequency and shortened contact times with increased running speed required more from the function of the neuromuscular system as well. This can be seen as increased EMG amplitudes both in the absolute and relative scales. This is due to increased voluntary (preprogrammed) activity, and the selection of the appropriate patterns depends on information coming from muscles, joints, and associated tissues, mediated by proprioceptive reflex systems (5). Thus, the proprioceptive input modifies EMG activity in the leg muscles in connection with changes in muscle tension (8). With shortening contact time at greater running speeds, the functional role of reflexes might become even more important for powerful force production.

In the present study, the increased coactivity of agonist and antagonist muscles (VL vs. BF and GA vs. TA) just before and after touchdown suggests increased knee and ankle joint stiffness in the beginning of the contact phase. In the late stance phase, however, the activity of leg extensors almost disappeared early before the toe-off, suggesting rebound phenomenon due to the active state of muscles in the previous phases. During preactivity (13) and braking phases, the muscles actively generate high tension that can be released passively during the push-off phase. Good coordination between muscles requires certain relaxation times (24), which might explain partly the silent period of leg extensor muscles in the end-of-stance phase.

The greatest and longer-lasting change in the muscle activity of the BF muscle with increasing speed may be responsible for further force production in the contact phase when extending the hip joint. Simonsen et al. (24) have suggested that during the ground contact the hamstring muscles can release the elastic energy stored during flight when they function eccentrically. The relative lengthening of the hamstring activity during the stance phase with increasing running speed may emphasize the role of the hamstring muscles to drive the body powerfully forward. In the present study, the finding that the push-off force in the horizontal direction greatly influences running speed gives further support for this interpretation.

The vertical and horizontal forces in the present study are slightly higher than in the earlier finding (20). Their maximal values varied from 2.7–3.5 BW and from 0.4–1.1 BW with increasing running speed. One might expect that running is a 2-dimensional movement; however, mediolateral forces are produced as well. These forces varied from 0.05–0.1 BW in the present study, which are slightly smaller compared with the values in the literature (4). In addition, the present study demonstrated fast and short force production to the medial direction in the beginning of the contact followed by a longer-lasting outward force. This might be a natural running strategy of a human being, but, of course, interindividual variability exists.

In conclusion, a powerful force production in the optimal direction with increasing running speed requires increased muscle activity of the leg extensors in the preactivity and braking phases with longer-lasting increased activity of the hamstring muscles. Simultaneously, the muscular coactivity around the knee and ankle joints increases. Therefore, a good running technique with increasing speed can be described as increased joint stiffness around the knee and ankle joints when both the extensor and flexor muscles play an important role.

Practical Applications

Powerful force production in running requires that all affecting forces must be applied with the proper timing and in the intended line of motion. In other words, all unnecessary body movements should be eliminated. For achieving optimal running technique, a runner requires highly developed motor control. The results of the present study emphasize the role of agonist and antagonist muscles in creating high joint stiffness in the beginning of touchdown, which may prevent unnecessary yielding of the ankle, knee, and hip joints. In the push-off phase, the importance of hamstring muscles must be emphasized.

For additional improvement in running technique, it could be recommended that a runner develops powerful hip extensor muscles (hamstrings and gluteus), which bring about the leg movement downward and backward. This must be complemented with stiff joints in the beginning of the contact phase to optimize the braking action for the subsequent push-off phase. For training programs, this means special strength training and numerous repetitions of coordination drills.

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