

# A kinematic comparison of overground and treadmill running

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## ABSTRACT

NIGG, B. M., DE BOER, R. W., and V. FISHER. A kinematic comparison of overground and treadmill running. *Med. Sci. Sports Exerc.*, Vol. 27, No. 1, pp. 98–105, 1995. Treadmills are often used in research projects to simulate overground locomotion, assuming that locomotion is similar on a treadmill and overground. The purpose of this investigation was to determine whether a treadmill could be used to simulate overground locomotion. Twenty-two subjects ran on four different surfaces: overground and three treadmills that differed in size and power. The kinematics of the right leg and foot were studied using two high-speed Locam cameras (lateral and posterior view). The subjects ran in two different shoes at four different speeds (3.0–6.0 m·s<sup>-1</sup>). The differences in the kinematics between treadmill and overground running could be divided into systematic and subject dependent components. Subjects systematically planted their feet in a flatter position on the treadmill than overground. Most of the lower extremity kinematic variables, however, showed inconsistent trends for individual subjects, depending on the individual subject's running style, running speed, and shoe/treadmill situation. The differences were substantial. It is not yet understood how the human locomotor system adapts to a particular treadmill running situation. However, it is concluded that individual assessment of running kinematics on a treadmill for shoe or shoe orthotic assessment may possibly lead to inadequate conclusions about overground running.

LOWER EXTREMITY, RUNNING SPEED, SHOE

Walking and running on treadmills is convenient for exercise testing and scientific research. Studies using treadmills allow for a controlled environment and are, therefore, often used for locomotion research. The underlying assumption when using a treadmill for scientific studies is that locomotion on a treadmill is similar to locomotion overground. However, metabolic, electromyographic, and biomechanical studies comparing overground and treadmill locomotion are not consistent in their discussion of this assumption. Some studies support, others challenge, the above assumption (2,3,5,7,10,11,21).

Nelson et al. (10) used high-speed cinematography to compare selected biomechanical variables during overground and treadmill running. The results of their study including 16 competitive male runners with treadmill experience at a running speed of 6.4 m·s<sup>-1</sup> and a 0% slope showed longer periods of support, smaller vertical velocity of the center of mass, and less variation in vertical and horizontal velocities of the center of mass for treadmill compared with overground running. They also found significant differences between some selected kinematic variables for treadmill and overground running.

Dal Monte et al. (4) used three middle-distance athletes with extensive treadmill experience for a biomechanical comparison between treadmill and overground running. Despite some differences (less vertical movement of the center of mass, and decreased period of nonsupport and stride length during treadmill running) they concluded that the treadmill can be used as a specific simulator for middle-distance running at speeds typically employed during competitions.

Elliot and Blanksby (7) used high-speed cinematography with 24 experienced treadmill runners running at different speeds. With slow jogging speeds (3.3–4.8 m·s<sup>-1</sup>) they found a shorter stride length, higher stride rate, and a shorter nonsupport period during treadmill running compared with overground running.

Sykes (17) found greater hip and knee extension at toe-off and increased ankle range of motion on the treadmill for a single subject running at 6.9 m·s<sup>-1</sup>. In a study measuring the electromyographic activity of some lower limb muscles, similar patterns were found when comparing overground with treadmill running (16).

Winter (19,20) noted that the average velocity of the center of mass in a laboratory coordinate system is zero and that during treadmill running, the velocity used for kinetic energy calculations is not a real value, but a simulated one. It was shown that the vertical displacement and velocity of the center of mass are similar in both

running situations. Furthermore, Winter hypothesized that the runner would receive energy from the treadmill at foot contact, and that the runner would impart energy to the belt at toe-off due to the propulsive forces of the foot.

Van Ingen Schenau (9), however, using a theoretical mathematical approach, showed that the mechanics of treadmill running and overground running are basically the same if the speed of the treadmill belt is constant. It was suggested that differences found in some studies may be due to differences in air resistance, which was previously found by Pugh (13), and/or differences in perceptual processes as indicated by Schmidt (15). Elliot and Blanksby (7) concluded, with respect to this point, that experience with treadmill running is an important factor when studying the biomechanics of treadmill running.

Dillman (5) reviewed the literature on the kinematics and energy cost differences between overground and treadmill running and concluded that there are no outstanding differences between the two modes of running. In a study of treadmill sprinting using five sprinters with treadmill experience, Frishberg (8) suggested that the moving treadmill belt decreased the energy required to propel the body by bringing the supporting foot and leg back under the body during the support phase of running.

In a review on the biomechanics of running, Williams (18) concluded that when significant differences were reported, they have generally been for speeds greater than  $5.0 \text{ m}\cdot\text{s}^{-1}$ . However, the majority of comparisons between treadmill and overground running showed nonsignificant differences. It was emphasized that only rare differences in angular kinematics of the limbs have been measured. However, definitive knowledge of movement adaptations of a runner to the treadmill is still not available.

One of the sources of variation between treadmill and overground running, and the inconsistent findings in the literature, might be related to the different treadmills used. Two aspects dealing with the treadmill itself are discussed in the literature: First, the treadmill must have a strong enough driving mechanism so that the energy transfer between the subject and the belt is minimized (9,20); and second, the construction of the treadmill must be so that the perceptual information during treadmill running is close to the one received during overground running (15). The sense of balance can be influenced by design factors such as running surface size, height of the treadmill, and a railing for support. It is speculated that larger, more expensive treadmills, typically designed for research and high-performance testing, fulfill these requirements to a greater extent than smaller and less expensive treadmills, typically designed for physical fitness-related situations. It may be speculated that, com-

pared with overground running, the running style will change more while running on a small treadmill than on a larger treadmill.

Treadmills are often used for research on sport shoes and shoe orthotics. Based on the conflicting information in the literature, it appears valid to question the value of using the treadmill to answer questions related to sport shoe construction and/or shoe orthotics. One may want to answer the question when studying aspects of shoe and design or shoe orthotic fitting, whether or not the use of a treadmill assessment may hide or unpredictably change some of the important factors tested.

The purpose of this study was to determine whether a treadmill can be used as a valid instrument to simulate the kinematics of human locomotion during overground running. Specifically, leg kinematics were quantified for treadmill running by varying the treadmill, the running velocity, the shoe, and the experience with treadmill running and were compared with the corresponding values for overground running.

## METHODS

Twenty-two subjects (11 runners and 11 nonrunners) provided written, informed consent to participate in the study. The runners (mass  $70.3 \pm 6.9 \text{ kg}$ , height  $179.6 \pm 3.4 \text{ cm}$ ) were members of a local running club and ran  $5.8 \pm 2.4 \text{ times}\cdot\text{wk}^{-1}$  for  $70.9 \pm 37.7 \text{ km}\cdot\text{wk}^{-1}$ . Most of the runners had previous experience with treadmill running. The nonrunners (mass  $76.4 \pm 9.1 \text{ kg}$ , height  $177.4 \pm 7.5 \text{ cm}$ ) were physically active but were never involved in systematic running. Most nonrunners had no experience with treadmill running. Before data collection, the subjects ran on the treadmill until they felt comfortable and did not require assistance of the railings. Special attention was paid to a proper warming up period prior to the testing sessions. The subjects performed tests on four different running surfaces: normal overground running on a sport surface (OG), running on a large treadmill (Q2), running on a midsize treadmill (Q6), and running on a small treadmill (A). OG-running was done in the laboratory on a sport surface with a running lane of approximately 30 m. Treadmill running was done with 0% grade slope of the running surface. The large Q2-treadmill had a running area of  $2.0 \text{ m} \times 0.6 \text{ m}$ , a maximal speed of  $8 \text{ m}\cdot\text{s}^{-1}$ , and a 2.5-kW motor. The midsize Q6-treadmill had a running area of  $1.65 \text{ m} \times 0.51 \text{ m}$ , a maximal speed of  $8 \text{ m}\cdot\text{s}^{-1}$ , and a 2.5-kW motor. The small A-treadmill had a running area of  $1.3 \text{ m} \times 0.4 \text{ m}$ , a maximal speed of  $4.5 \text{ m}\cdot\text{s}^{-1}$ , and a 1.1-kW motor.

For each running situation, the subject wore two different shoes: a standard running shoe (called laboratory shoe) provided by the laboratory, and their personal running shoes.

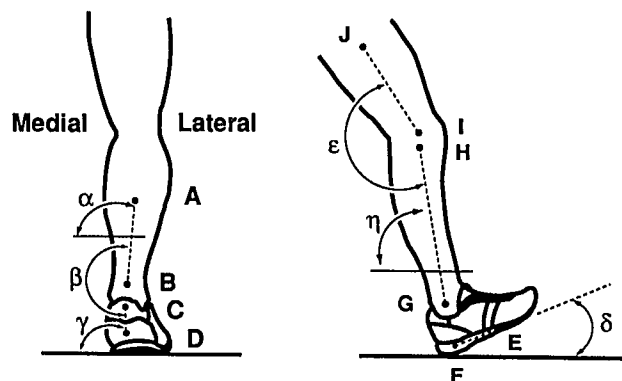


Figure 1—Illustration of the landmarks used on leg and shoe and the angles derived from film analysis using these landmarks.

The runners were tested for the four running speeds: 3.0, 4.5, 5.0, and 6.0  $\text{m}\cdot\text{s}^{-1}$  for all except the A-treadmill and for the running speeds 3.0 and 4.5  $\text{m}\cdot\text{s}^{-1}$  for the A-treadmill. The nonrunners ran only at the two lower speeds (3.0 and 4.5  $\text{m}\cdot\text{s}^{-1}$ ) during OG- and A-running. This selection was necessary because the A treadmill had a maximal speed of 4.5  $\text{m}\cdot\text{s}^{-1}$  and for safety reasons for the less experienced nonrunners. The order of treadmill, shoe, and speed conditions was randomized. During OG-running, speed was measured with photo cells, and trials with more than 5% deviation from the nominal speed were rejected. During treadmill running, the speed was set using the calibrated treadmill control unit.

At least three complete strides were filmed at each treadmill speed. One trial per subject per condition (surface, shoe, speed) for each of the 11 subjects comprising the runner and nonrunner groups was used in the analysis. This procedure was selected since the intraindividual standard deviations determined for four arbitrarily selected subject-treadmill combinations were rather small (between 0.3° and 1.0° for  $\alpha_0$ , between 1.0° and 1.3° for  $\delta_0$ , between 2.3° and 2.9° for  $\epsilon_0$ , and between 0.6° and 2.3° for  $\Delta\gamma_{\text{avr}}$ ).

The kinematics of the right leg and foot were determined by film analysis using two high-speed Locam 16-mm cine cameras running at a nominal frequency of 100  $\text{frames}\cdot\text{s}^{-1}$ . The shoes and the test subjects were prepared as illustrated in Figure 1. The posterior markers on the shoe were placed so that the line between these two markers and the horizontal formed an angle of 90° in the unloaded shoe (11). One marker on the lower leg was placed on the Achilles tendon just above the shoe. The second marker was located 15 cm above this point in the center of the calf in the standing position. Using these markers, the leg angle  $\alpha$  (angle between the leg and the ground on the medial side from posterior), the Achilles tendon angle  $\beta$  (angle between the leg and the heel on the medial side from posterior), and the rear foot angle  $\gamma$  (angle between the heel of the shoe and the ground on the medial side from posterior) were determined. The lateral

markers were located as follows (12): Marker E was placed on the midsole of the forefoot at the head of the fifth metatarsal, marker F on the midsole of the heel underneath the calcaneus, marker G on the lateral malleolus, marker H on the head of the fibula, marker I just above the tibio-femoral joint midline for a lateral view in the standing position, and marker K on the midline of the upper leg two-thirds of the distance between the tibio-femoral and the hip joint. From these lateral markers, the shoe sole angle  $\delta$  (angle between the shoe sole and the running surface from lateral), and the knee angle  $\epsilon$  (angle between the leg and the thigh from lateral) were calculated. Data analysis was performed during ground contact only.

The high speed film was digitized on a Hewlett Packard digitizer using the markers previously described. The markers were projected into the x-z plane (posterior view) and y-z plane (lateral view) to calculate the angles using a weighted smoothing over five points. The angle values in the lateral and posterior view are projections into the respective planes. Their values are influenced by abduction and/or adduction of the foot (1). Errors due to positioning of the markers were smaller than 0.1° (12). Errors due to digitization were smaller than 2°.

The variables chosen for analysis describe the initial conditions from a posterior and lateral view and the relative changes of these angles during ground contact.

### Statistical Analysis

The differences between overground and treadmill running were tested for each of the shoe, speed and treadmill situations using a four way analysis of variance for repeated measures (6). A significance level of 1% was used.

The initial statistical analysis dealt with the complete set of data for runners and nonrunners with eight situations per subject. A four-way analysis of variance for repeated measures with 11 runners, 11 nonrunners, 2 surfaces (overground and A-treadmill), 2 shoes (personal shoe and laboratory shoe), and 2 speeds (3  $\text{m}\cdot\text{s}^{-1}$  and 4.5  $\text{m}\cdot\text{s}^{-1}$ ) was run on the data.

The second analysis included only the runners group who had complete data for three surfaces (overground, Q6, and Q2 treadmills), four speeds (3, 4.5, 5, and 6  $\text{m}\cdot\text{s}^{-1}$ ), and two shoes (personal and laboratory).

## RESULTS AND DISCUSSION

Results and discussion are presented in two sections: first, for the group mean values, and second, for individual values.

### Results for Group Mean Values

The results for the mean values with standard error for the runners at 3  $\text{m}\cdot\text{s}^{-1}$  running in their personal shoes are

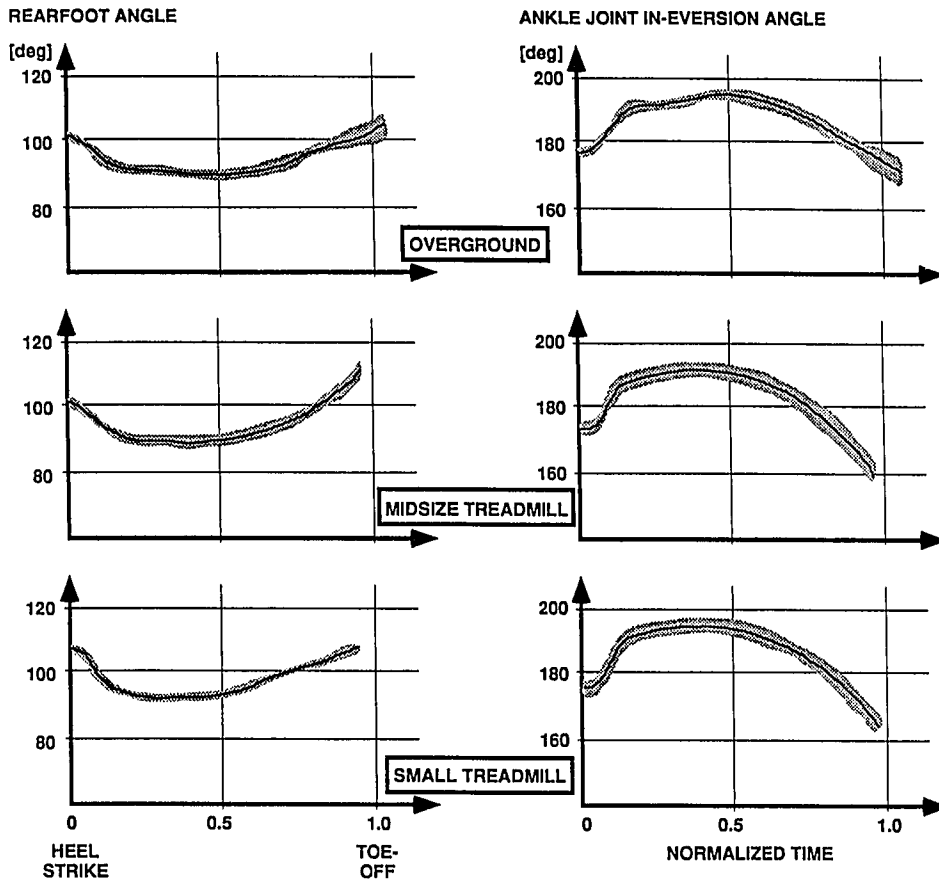


Figure 2—Illustration of selected kinematic results for the runners ( $N = 11$ ) running in their personal shoes at a speed of  $3.0 \text{ m} \cdot \text{s}^{-1}$ . Shown are the rear foot angle (left) and the ankle joint in-eversion (right) for overground running (top), running on a midsize Q6-treadmill (middle) and running on a small A-treadmill (bottom). The kinematic variables show mean and standard error and are normalized for stance time with the time 0 corresponding to touch-down and the time 1 corresponding to take-off. Rearfoot eversion is defined for angles  $> 90^\circ$ , rearfoot inversion for angles  $< 90^\circ$ . Ankle joint inversion is defined for angles  $< 180^\circ$ , ankle joint eversion for angles  $> 180^\circ$ .

illustrated for the rear foot angle,  $\gamma$ , and the ankle joint in-eversion,  $\beta$  (Fig. 2).

Both multivariate and univariate analysis of the data showed that there was no significant difference in lower leg movement between the nonrunners and runners. There were interactions between shoe and skill, speed, and shoe and speed, surface, and shoe. The analysis of variance for repeated measures showed interactions only between the surface and shoe at the speed of  $4.5 \text{ m} \cdot \text{s}^{-1}$ . Subsequent analysis did not combine data where interactions were present. The within factor of shoe was controlled when analyzing surface differences and speed differences. Once this was done, no further interactions were present. Consequently, the following presentation of the results and their discussion will concentrate on the influences of surface, speed, and shoe.

**Surfaces (overground and treadmills).** To test for the main effects of the different surfaces, the trials with the laboratory shoes were used in the analysis of variance to control for shoes. For this situation, there was no interaction for the remaining within factors (surface, speed) or their combinations. The subsequent analysis of variance showed a significant difference between overground and treadmill running. For the nonrunners and runners the initial leg angle,  $\alpha_0$ , showed a significant but small ( $98.0^\circ$  to  $99.8^\circ$ ), the initial shoe sole angle,  $\delta_0$ , a

significant but large difference ( $15.9^\circ$  to  $8.0^\circ$ ) between overground and A-treadmill running. The large difference for the shoe sole angle,  $\delta_0$ , between OG- and A-treadmill running was confirmed by the results for the personal shoe ( $14.9^\circ$  to  $7.9^\circ$ ).

Analysis of the runners in the laboratory shoe showed additional significant differences between treadmill and overground running for the ankle joint inversion (from maximal eversion position to take-off),  $\Delta\beta_{\text{inv}}$  ( $-27.8^\circ$ ,  $-30.2^\circ$ , and  $-25.0^\circ$  for OG, Q6, and Q2, respectively), and for the rear foot eversion (from touch-down to maximal eversion position),  $\Delta\gamma_{\text{evr}}$  ( $-17.8^\circ$ ,  $-19.3^\circ$ , and  $-20.4^\circ$  for OG, Q6, and Q2, respectively).

In the attempt to understand the effect of treadmills on running kinematics, the subjects were not forced into a prescribed running style. This led to the result that some subjects changed their landing style from heel to midfoot or forefoot landing when changing speed, shoe, and/or surfaces. To eliminate this effect an analysis of variance was run including only those subjects who landed consistently with the heel first ( $N = 14$ ). The multivariate analysis of variance revealed no significant differences between surfaces when the landing style was controlled for, even though  $\alpha_0$  and  $\delta_0$  were still significantly different in the univariate analysis. Again there were no interactions among the factors skill, surface, and speed.

A simple effects analysis was included to study if runners and nonrunners adapted similarly to the overground and A-treadmill. Runners had no significant differences between overground and A-treadmill running whereas nonrunners had a significant decrease in the shoe sole angle by  $5.4^\circ$  at the slower running speed of  $3 \text{ m}\cdot\text{s}^{-1}$  and  $4.2^\circ$  at  $4.5 \text{ m}\cdot\text{s}^{-1}$ .

When the runners group was controlled for landing style as well as shoe, the results showed significant but small differences for the shoe sole angle,  $\delta_o$  (19.0, 16.7, and 16.9 for OG, Q6, and Q2, respectively) and the rear foot eversion,  $\Delta\gamma_{\text{evr}}$  (15.5, 16.7, 18.7 for OG, Q6, and Q2, respectively).

The effect of the "quality" of a treadmill on lower extremity kinematics was tested by comparing the four surfaces: Overground, A-treadmill (small), Q6-treadmill (midsize), and Q2-treadmill (large) at the two slower speeds ( $3 \text{ m}\cdot\text{s}^{-1}$  and  $4.5 \text{ m}\cdot\text{s}^{-1}$ ). The analysis of variance for repeated measures showed no significant differences between overground running and treadmill running.

An analysis of the results for OG, Q6, and Q2 across all speeds showed the greatest difference between results from overground and from the Q2-treadmill, the large research treadmill. The simple effects test (7) showed that the shoe sole angle,  $\delta_o$ , was different between overground running and the Q6-treadmill whereas the ankle joint eversion,  $\Delta\beta_{\text{evr}}$ , the knee angle,  $\epsilon_o$ , and the rear foot eversion,  $\Delta\gamma_{\text{evr}}$ , were different between overground and the Q2-treadmill. There were, however, no significant differences between the two treadmills.

**Speed.** Significant differences in lower leg kinematics between overground and treadmill running were generally reported for speeds greater than  $5 \text{ m}\cdot\text{s}^{-1}$  (19). This was not verified by the results of this study. The effect of surfaces was tested for each running speed for the laboratory shoe. The simple effects analysis (7) showed that the differences in the lower leg variables analyzed were at the speeds of  $3 \text{ m}\cdot\text{s}^{-1}$  and  $4.5 \text{ m}\cdot\text{s}^{-1}$ . The leg angle,  $\alpha_o$ , the shoe sole angle,  $\delta_o$ , and the knee angle,  $\epsilon_o$ , varied for the different surfaces. However, no differences were found between surfaces at the higher speeds,  $5 \text{ m}\cdot\text{s}^{-1}$  and  $6 \text{ m}\cdot\text{s}^{-1}$ . Some of these results were confirmed for the personal shoes. Running at  $3 \text{ m}\cdot\text{s}^{-1}$  showed significant differences in  $\alpha_o$  and  $\delta_o$ , running at  $4.5 \text{ m}\cdot\text{s}^{-1}$  in  $\alpha_o$ , and running at  $5 \text{ m}\cdot\text{s}^{-1}$  in  $\alpha_o$ , and  $\epsilon_o$ . No differences were seen between surfaces at  $6 \text{ m}\cdot\text{s}^{-1}$ .

**Shoe.** The nonrunners showed a significant difference in the shoe sole angle,  $\delta_o$  ( $11.8^\circ$  and  $14.6^\circ$  for personal and laboratory shoe, respectively). The runners showed significant differences in the ankle joint eversion,  $\Delta\beta_{\text{evr}}$  ( $20.7^\circ$  and  $23.9^\circ$  for personal and laboratory shoe respectively), the initial rear foot eversion,  $\Delta\gamma_{10}$  ( $-4.7^\circ$  and  $-7.0^\circ$  for personal and laboratory shoe, respectively), and the maximal rear foot eversion,  $\Delta\gamma_{\text{evr}}$  ( $-15.6^\circ$  and  $-19.2^\circ$  for personal and laboratory shoe, respectively).

## Discussion for Group Mean Values

The primary purpose of this investigation was to determine whether a treadmill can be used as a valid instrument to simulate overground running. If possible systematic differences between treadmill and overground running are known, extrapolation of the treadmill results to a normal overground running situation would be possible. However, if possible differences are not systematic and depend on factors such as landing style, speed, shoe, and/or treadmill used, a transfer of the results of treadmill experiments to a normal overground situation would not be appropriate. For example, if one is interested in maximal eversion or inversion for a certain shoe design, treadmill running and the adaptations of different individuals to the treadmill used might provide the wrong information about the actual situation during normal overground running. This could lead to faulty conclusions about the quality of a shoe.

**Surfaces (overground and treadmills).** The kinematic variables that showed significant differences between treadmill and overground running were: the initial shoe sole angle,  $\delta_o$ , initial leg angle,  $\alpha_o$ , the ankle joint inversion,  $\Delta\beta_{\text{inv}}$ , and the rear foot eversion,  $\Delta\gamma_{\text{evr}}$ .

While running on a treadmill, the subjects had in the average a smaller shoe sole angle than when running overground. This strategy for treadmill running required less time for the foot to gain full contact with the treadmill surface. It may be speculated that this adaptation is done by the subjects to provide an increased "feeling of stability." Support for this suggestion may be found in the fact that 8 of the 22 subjects changed their running style from normal heel landing to midfoot landing when changing from overground to treadmill running. However, even when the type of landing was controlled for, a decrease in the shoe sole angle from overground running to treadmill running was observed. Depending on the grouping this difference varied from  $7^\circ$  to  $3^\circ$ . This decrease in the shoe sole angle has an influence on the subsequent movement of the foot and leg, which is described by variables such as the initial ankle joint eversion,  $\Delta\beta_{10}$ , the total ankle joint eversion,  $\Delta\beta_{\text{evr}}$ , the ankle joint inversion,  $\Delta\beta_{\text{inv}}$ , the initial rear foot eversion,  $\Delta\gamma_{10}$ , and the total rear foot eversion,  $\Delta\gamma_{\text{evr}}$ . However, these variables are typically used in the assessment of the biomechanical quality of shoes and/or the effects of shoe orthotics.

The simple effects analysis holding skill showed no significant surface differences for the runners but a decrease in the shoe sole angle,  $\delta_o$ , for the nonrunners. Since the runners were experienced on the treadmill whereas the nonrunners had no experience, the data would suggest that practice might eliminate major differences in overground to treadmill running. However, when we examined the additional runner data and looked at the results of an analysis of variance of this group, we

found that the initial leg angle,  $\alpha_o$ , the ankle joint inversion,  $\Delta\beta_{inv}$ , and the rear foot eversion,  $\Delta\gamma_{evr}$ , were significantly different. Once both landing style and shoe were controlled, the runners still showed a significant difference for surfaces in the shoe sole angle,  $\delta_o$ , and the rear foot eversion,  $\Delta\gamma_{evr}$ . The fact that the significant variables change when shoe and landing style are controlled confirms that both factors are important if one wants to make inferences from a treadmill situation to an overground situation. This result emphasizes the importance of training on a treadmill and controlling the landing style.

Speculations from the literature regarding speed (18) and size of the treadmill (9,15,20) were not confirmed. The results of this study do not provide any support for the suggestion that running speed on the treadmill increased the kinematic differences between overground and treadmill running, or that changes in running kinematics would increase with decreasing size and/or power of the treadmill. In fact just the reverse was found. There were larger differences between overground running and the Q2-treadmill running than between overground and A-treadmill running. When examining the influence of speed on surface differences, significant differences between overground and treadmill running occurred at 3, 4.5, and 5  $m \cdot s^{-1}$ . However, there were no differences between surfaces at the speed of 6  $m \cdot s^{-1}$ .

It must be pointed out, however, that the number of subjects used to assess these questions was small ( $N = 22$  or less depending on the grouping used) and the variance associated with the variables was quite high. This must be considered when interpreting the results since the small sample size may not be representative of the total population and differences may either overestimate or underestimate real population differences. Because so few variables showed a significant difference, it may be by chance rather than a true representation of within factor differences.

**Results and Discussion for Individual Adaptations**

A result that differences in mean values are small does not imply automatically that differences for individuals are small too. The following analysis has the purpose to illustrate possible changes in lower extremity kinematics induced by the change from overground to a treadmill or due to changes between treadmills. The subjects and variables discussed in the following paragraphs were arbitrarily selected to illustrate the potential of treadmills to simulate overground running.

**Surfaces (overground and treadmills).** Aspects of eversion and inversion in the ankle joint can be described by the ankle joint inversion,  $\Delta\beta_{inv}$ , and by the initial ankle joint eversion,  $\Delta\beta_{10}$ . The individual results of four subjects in these two variables during treadmill and overground running show (Figs. 3 and 4) that the

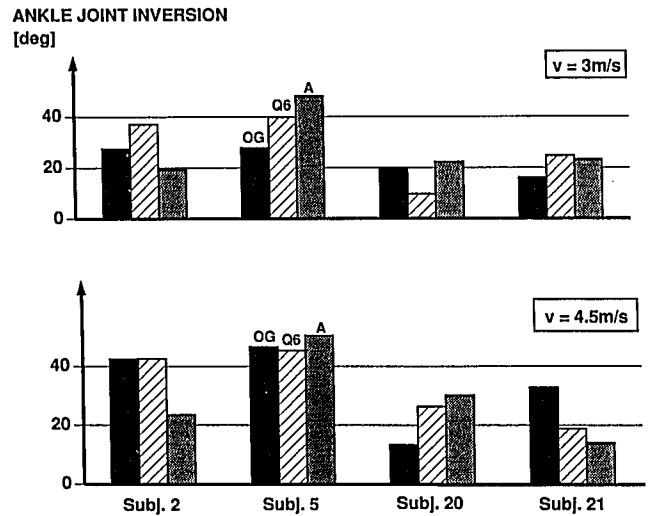


Figure 3—Individual changes in the ankle joint inversion for four selected subjects during Q6-treadmill, A-treadmill, and OG-running at a running speed of 3.0  $m \cdot s^{-1}$  (top) and 4.5  $m \cdot s^{-1}$  (bottom).

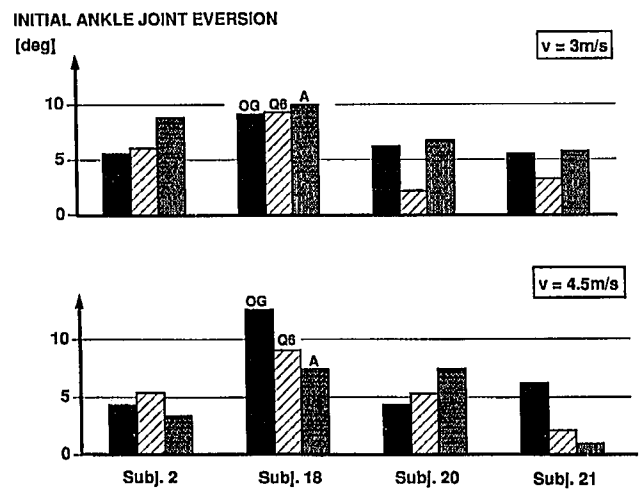


Figure 4—Individual changes in the initial ankle joint eversion for two selected subjects during Q6-treadmill, A-treadmill, and OG-running at a running speed of 3.0  $m \cdot s^{-1}$  (top) and 4.5  $m \cdot s^{-1}$  (bottom).

changes are substantial and inconsistent for the different subjects. Subject 21, for instance, showed about 8° more ankle joint inversion on the two treadmills than on overground for running at 3  $m \cdot s^{-1}$  and just the opposite pattern (higher ankle joint inversion for overground compared with treadmill running) for running at 4.5  $m \cdot s^{-1}$ . Subject 18, for instance, showed a constant initial ankle joint eversion,  $\Delta\beta_{10}$ , of about 9°–10° at a running speed of 3  $m \cdot s^{-1}$ , whereas the same subject showed a difference of about 6° in the same variable between overground and A-treadmill running at 4.5  $m \cdot s^{-1}$ .

Further examples could be added. They all support the same finding that individual adaptations to treadmills and/or speed were substantial and unpredictable. This agrees with the results of a recent study (14) in which large interindividual variability was found in a compar-

ison of treadmill running and running on grass using 3-D motion analysis and pressure measurement. At this point in time no information is available to explain the adaptation of a particular runner to a particular treadmill/speed/shoe running situation. It can, however, be concluded that the use of a treadmill can both overpredict and underpredict substantially foot and ankle joint eversion and inversion during running.

It should be noted that the initial ankle joint eversion variable,  $\Delta\beta_{10}$ , is relatively insensitive to the used 2-D method, whereas the ankle joint inversion variable,  $\Delta\beta_{inv}$ , is rather sensitive to slight movement changes during take-off. Some of the differences in  $\Delta\beta_{inv}$  may, therefore, be attributed to the methodology. However, this is not the case for the variable  $\Delta\beta_{10}$ .

**Speed.** Running speed has been described as an important factor for appropriate comparison between treadmill and overground running (7,18). Temporal factors like stride length and stride rate have been shown to change systematically with speed (18). The individual results of this study underline the importance of speed in the comparison of kinematic variables for overground and treadmill running. However, changes in leg kinematics for treadmill and overground running as a function of speed were unpredictable. Runners and nonrunners showed significant differences for changes in speed in the variables  $\Delta\beta_{cvr}$ ,  $\Delta\beta_{inv}$ ,  $\epsilon_o$ , and  $\Delta\gamma_{cvr}$ . Additionally, nonrunners showed significant differences for the variables  $\Delta\beta_{10}$ ,  $\gamma_o$ , and  $\Delta\gamma_{10}$ . However, individual differences were again not consistent. Subject 21, for instance, showed a difference between overground and Q6-treadmill running of about  $20^\circ$  in the ankle joint inversion,  $\Delta\beta_{inv}$ , for the running speed of  $5 \text{ m}\cdot\text{s}^{-1}$  but basically no difference in the same variable for the running speed of  $6 \text{ m}\cdot\text{s}^{-1}$  (Fig. 5). Subject 20, for instance, showed a higher value of ankle joint inversion for overground as compared with Q6-treadmill running for the speeds of 3 and  $6 \text{ m}\cdot\text{s}^{-1}$  but not for the speeds of 4.5 and  $5 \text{ m}\cdot\text{s}^{-1}$ .

Similar inconsistencies were found for other variables such as the initial change of the ankle joint eversion (Fig. 6).

**Shoe.** The design of the shoe is a factor which may influence the adaptation of a subject to treadmill running. The results of this study showed that the adaptations are inconsistent for different subjects and different treadmills (Fig. 7). Subject 18, for instance, showed in Q6 running only a small difference in the ankle joint inversion for the two shoes. However, the same subject for the same comparison showed in overground running a difference of more than  $12^\circ$ . Ankle joint inversion,  $\Delta\beta_{inv}$ , was higher in the laboratory shoes for subject 18, but the opposite was found for subject 20. For the initial ankle joint eversion,  $\Delta\beta_{10}$ , the situation was even more complicated because the adaptation was also dependent on the combination of shoe and treadmill. It can be concluded that the shoe influences the adaptation of an athlete while running on the treadmill and that the adaptation is tread-

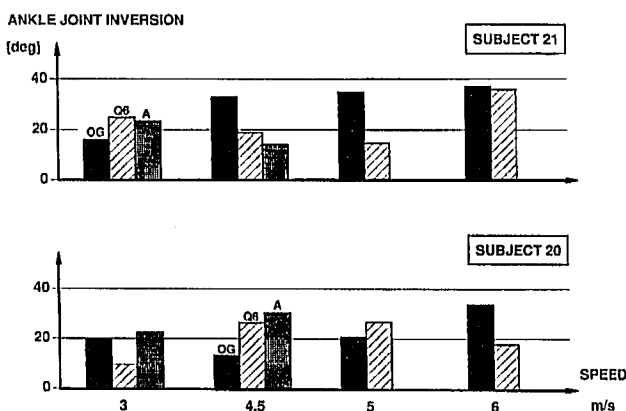


Figure 5—Illustration of changes in the ankle joint inversion during Q6-treadmill, A-treadmill and OG-running as a function of running speed for two arbitrarily selected subjects, subject 21 (top) and subject 20 (bottom).

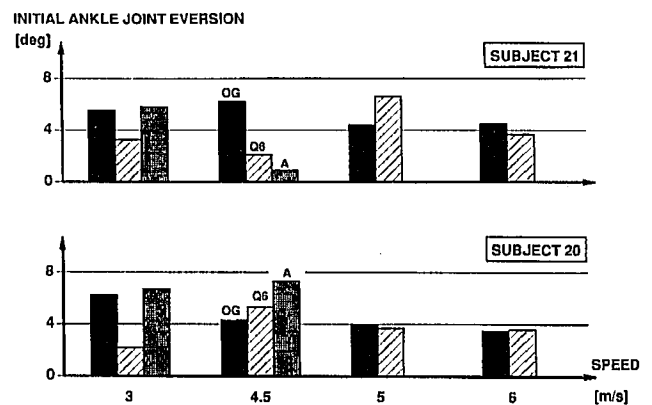


Figure 6—Illustration of changes in the initial ankle joint eversion during Q6-treadmill, A-treadmill, and OG-running as a function of running speed for two arbitrarily selected subjects, subject 21 (top) and subject 20 (bottom).

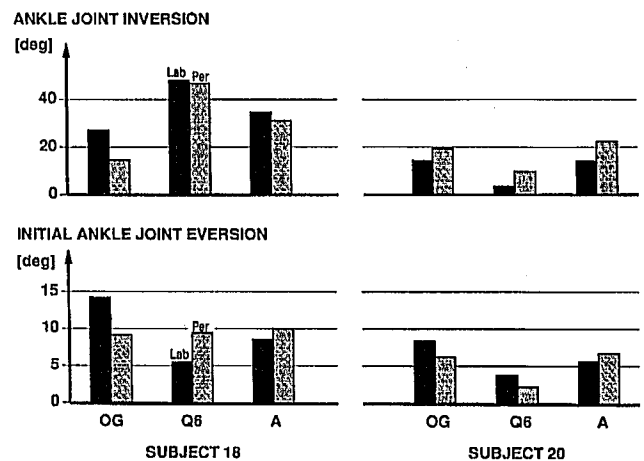


Figure 7—Illustration of changes in the ankle joint inversion (top) and the initial ankle joint eversion (bottom) for two arbitrarily selected subjects running in their personal and a laboratory shoe.

mill dependent. This, of course, suggests caution when using a treadmill to quantify the effects of shoes or shoe orthotics, when these results should be applied to overground running.

## CONCLUSIONS

The purpose of this study was to determine whether a treadmill can be used as a valid instrument to simulate the kinematics of human locomotion during overground running. The differences measured in kinematic variables between treadmill and overground running can be subdivided into systematic and subject dependent components. Subjects adapt their landing style in treadmill running systematically so that the foot lands in a more flat position than during overground running. This strategy may provide a touchdown during treadmill running that may be perceived as more stable by the runners.

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Most of the lower leg kinematic variables, however, show an inconsistent pattern depending on the individual athlete's landing style, running speed, and shoe/treadmill situation.

It is concluded that the use of a treadmill can both overpredict and underpredict aspects of ankle joint kinematics typically used to assess the quality of running shoes. The extrapolation of kinematic results from treadmill to overground running situations depends in an unsystematic pattern on the treadmill used, the running speed and the shoe. However, it is not yet understood how the human locomotor system adapts to a particular treadmill running situation.

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