

## Ground reaction forces at different speeds of human walking and running

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In this study the variation in ground reaction force parameters was investigated with respect to adaptations to speed and mode of progression, and to type of foot-strike. Twelve healthy male subjects were studied during walking (1.0–3.0 m s<sup>-1</sup>) and running (1.5–6.0 m s<sup>-1</sup>). The subjects were selected with respect to foot-strike pattern during running. Six subjects were classified as rearfoot strikers and six as forefoot strikers. Constant speeds were accomplished by pacer lights beside an indoor straightway and controlled by means of a photo-electronic device. The vertical, anteroposterior and mediolateral force components were recorded with a force platform. Computer software was used to calculate durations, amplitudes and impulses of the reaction forces. The amplitudes were normalized with respect to body weight (b.w.). Increased speed was accompanied by shorter force periods and larger peak forces. The peak amplitude of the vertical reaction force in walking and running increased with speed from approximately 1.0 to 1.5 b.w. and 2.0 to 2.9 b.w. respectively. The anteroposterior peak force and mediolateral peak-to-peak force increased about 2 times with speed in walking and about 2–4 times in running (the absolute values were on average about 10 times smaller than the vertical). The transition from walking to running resulted in a shorter support phase duration and a change in the shape of the vertical reaction force curve. The vertical peak force increased whereas the vertical impulse and the anteroposterior impulses and peak forces decreased. In running the vertical force showed an impact peak at touch-down among the rearfoot strikers but generally not among the forefoot strikers. The first mediolateral force peak was laterally directed (as in walking) for the rearfoot strikers but medially for the forefoot strikers.

Thus, there is a change with speed in the complex interaction between vertical and horizontal forces needed for propulsion and equilibrium during human locomotion. The differences present between walking and running are consequences of fundamental differences in motor strategies between the two major forms of human progression.

**Key words:** foot-strike type, ground reaction forces, human locomotion, speed adaptation.

During locomotion the action forces exerted by the feet on the ground are counteracted by reaction forces which provide for propulsion and equilibrium control. These forces can be separated into vertically, anteroposteriorly and medio-

laterally directed components and measured with a force platform. Different modes of progression show specific ground reaction force patterns. The analysis of ground reaction forces during locomotion can therefore give valuable information about basic locomotor mechanisms and provide data which can be used to evaluate normal as well as pathological gait.

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The basic patterns of reaction forces during locomotion have already been studied during the first half of this century (Amar 1916, 1920, Fenn 1930a, b, Elftman 1939). In more recent years several investigations have been devoted to the changes in amplitude and timing of ground reaction forces at different speeds in walking and running (walking, Andriacchi *et al.* 1977, Alexander & Jayes 1980; running, Roy 1982, Hamill *et al.* 1983, Frederick & Hagy 1986, Munro *et al.* 1987). Attention has also been given to subject variability and possible asymmetries in ground reaction forces between the legs during walking and running (Bates *et al.* 1983, Hamill *et al.* 1984). Still further investigations are needed in order to establish quantitative and qualitative reference data on reaction forces in walking and running over a wide velocity range.

A comparison between walking and running at comparable speeds has demonstrated a number of specific differences concerning kinematics and muscle activity patterns (Grillner *et al.* 1979, Thorstensson *et al.* 1982, 1984, Nilsson *et al.* 1985a). Earlier studies of ground reaction forces have been carried out separately on walking and running (see above), but no comprehensive comparison has been performed at the same speeds.

Several investigators have pointed out specific patterns in the reaction force curves related to foot-strike type at touch-down in running (rear-, mid- or forefoot strike). In general, these studies have been focused on only one type of foot-strike (Komi *et al.* 1987, Munro *et al.* 1987, Nigg *et al.* 1987). Investigations which directly compare different foot-strike types are few and limited to a single velocity (Cavanagh & LaFortune 1980, Clarke *et al.* 1983).

In this study the following questions were addressed: (1) How do the ground reaction

forces in walking and running vary over a wide range of speeds? (2) Which are the differences in ground reaction force patterns between walking and running at the same speeds? (3) Which are the differences in ground reaction forces between typical rear- and forefoot strikers in running at different speeds?

## MATERIALS AND METHODS

**Subjects.** Twelve healthy habitually active male students of physical education volunteered as subjects in the study. They were selected with respect to foot-strike pattern during running. Six subjects were classified, by means of film analysis, as forefoot strikers (strike ground with the anterior part of the foot first) and six as rearfoot strikers. Ages, heights and weights of the whole group and subgroups are presented in Table 1.

**Methods and procedure.** The subjects performed level walking and running over a force platform (Kistler, Type 9281B) located in the centre of an indoor wooden straightway (Fig. 1). Three orthogonal ground reaction force components were recorded:  $F_z$ , vertical force;  $F_y$ , anteroposterior (horizontal) force; and  $F_x$ , mediolateral (horizontal) force. The force platform was connected to a charge amplifier (Kistler, Type 9805), an analog FM tape recorder (Tandberg, Model TIR 115) and an ink-recorder (Siemens-Elema, Type Mingograph 803, Fig. 1).

The speeds were 1.0, 1.5, 2.0, 2.5, 3.0 m s<sup>-1</sup> in walking and 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0 m s<sup>-1</sup> in running. The speeds of the subjects were guided by pacer lights placed along the straightway at 1-m intervals (Fig. 1). The lamps were turned on in a sequential fashion at different frequencies, causing the light to propagate at different constant speeds which the subjects had to follow. In order to check that a constant speed was held over the force platform, four photocells (SICK, Type WL25-714), connected to a timing unit (Hego system 6000) were used (Fig. 1). The photocell beams were interrupted at head level in order to minimize the interference from the upper

Table 1. Mean values and ranges for ages (years), heights (m) and weights (kg) for the whole sample ( $n = 12$ ) and subsamples ( $n = 6$ )

	Age	Height	Weight
Whole sample	26	1.85	77
	20-32	1.74-1.97	71-90
Forefoot strikers	26	1.84	78
	22-32	1.74-1.90	71-88
Rearfoot strikers	26	1.86	76
	20-30	1.80-1.97	71-90

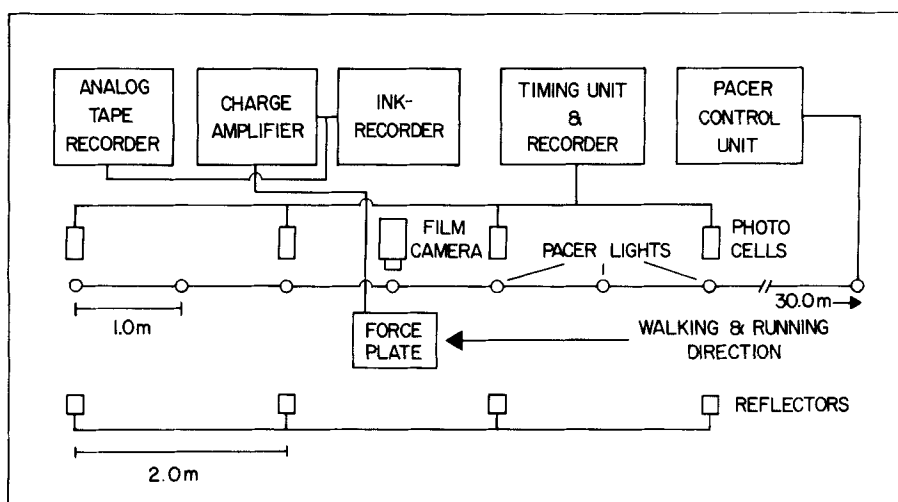


Fig. 1. Schematic presentation of the experimental set-up. Description in text (see Methods).

extremities. The distance between each photocell was 2 m, forming three intervals equally spaced with respect to the centre of the force platform (Fig. 1). The mean speed in the intervals was not allowed to differ more than 8% from the stipulated speed. The actual speed deviations were on average 3.7% (0.04 and 0.22 m s<sup>-1</sup> at 1.0 and 6.0 m s<sup>-1</sup> respectively).

The subjects wore shorts and sport shoes (Karhu TBA) with the mid-sole wedges removed, i.e. the soles were of uniform thickness (12 mm). These shoes were used in order to reduce the influence of an elevated heel on the natural foot-strike pattern. To enable the determination of consecutive support times, and thereby average stride cycle durations ( $T_c$ ), the shoes were equipped with pressure-sensitive devices (Nilsson *et al.* 1985 b). A pressure transducer (National Semiconductor LX0503A) was connected to a flexible silicone tube glued to the outer perimeter of the sole. Deformation of the tubing from foot/floor contact caused a change of pressure inside the tube, which was converted to a voltage change via the transducer. The pressure transducer signals were transmitted to a receiver by means of a telemetry system (Medinik, Type IC-600-DC-G) and recorded with an ink-recorder (Siemens-Elema, Type Mingograph 803). The stride cycle duration ( $T_c$ ) was calculated from the two strides closest to the passage over the force plate. The support phase duration ( $T_{su}$ ) was measured from the force-time curves of the reaction force recordings. The subjects were given several practice trials at each speed to get used to the speed control and to learn to land on the force platform with the right foot without any unnatural adjustments of the stride. Each foot-strike on the force platform was filmed at 50 frames

s<sup>-1</sup> for later verification of the pre-defined foot-strike pattern.

**Data processing and analysis.** The ground reaction force components ( $F_x$ ,  $F_y$  and  $F_z$ ) were replayed at the recording speed and transferred from the analog tape recorder via a 12-bit A/D converter to an HP 1000 computer. One set of ground reaction forces ( $F_x$ ,  $F_y$  and  $F_z$ ) per subject and speed was analysed, giving a total of 60 sets in walking (12 subjects  $\times$  5 speeds) and 42 sets per foot-strike group in running (6 subjects  $\times$  7 speeds).

Computer software was used to calculate durations, amplitudes and total impulses (areas under the force-time curve) of the selected reaction force parameters. The start and stop of the support phase were automatically defined from the vertical force ( $F_z$ ) by means of computer software. The manual marking of the other reaction force events was done with the aid of interactive software and the cursor facilities of the terminal (Tektronix 4010). The amplitudes of the reaction forces were normalized to multiples of body weight (b.w.), i.e. the vertical reaction force during quiet standing.

Conventional statistical methods were used to calculate means and standard deviations (SD). Differences were tested for significance with the Student's *t*-test.

## RESULTS

### (1) General description

Figure 2 shows typical recordings of the vertical ( $F_z$ ), anteroposterior ( $F_y$ ) and mediolateral ( $F_x$ )

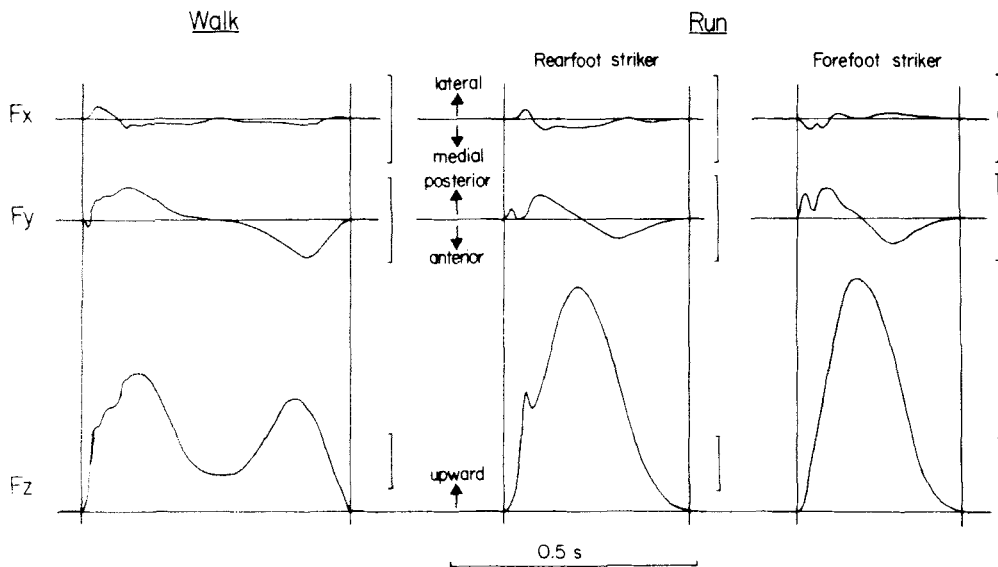


Fig. 2. Representative recordings of the mediolateral ( $F_x$ ), anteroposterior ( $F_y$ ), and vertical ( $F_z$ ) ground reaction forces of the right foot during walking and running with rearfoot and forefoot strike at  $2.0 \text{ m s}^{-1}$ . The vertical bars represent 500 N. Note the different calibration settings for the vertical and horizontal reaction forces.

ground reaction force curves in walking, and in running with rearfoot and forefoot strike at  $2 \text{ m s}^{-1}$ .

**Walking.** The vertical reaction force in walking typically showed two peaks with an interjacent trough. The anteroposterior (horizontal) reaction force curve had a small initial force peak in the anterior direction followed by a posterior-directed braking force which changed into a propulsive horizontal force at about mid-support. The rising phase of the first vertical and the braking horizontal force sometimes had small superimposed peaks predominantly at high speeds. The mediolateral reaction force always showed a brief laterally directed peak at foot-strike (i.e. the action force from the right foot was in the medial direction), followed by a mainly medially directed reaction force during the main part of the support phase.

**Running.** The shape of the vertical reaction force in running differed between the two types of foot-strike. The rearfoot strikers always had an initial impact peak (small at low speeds) which the forefoot strikers, as a rule, were lacking. The anteroposterior braking force curves always had double peaks among the forefoot

strikers. This was also the dominating pattern among the rearfoot strikers (in 37 of 42 recordings). The double peaks were, however, less prominent among the rearfoot strikers. The mediolateral force had a relatively complex course and the two foot-strike types differed mainly in the first part of the support phase. The forefoot strikers always had an initial medially directed reaction force peak, whereas the rearfoot strikers showed a typical laterally directed peak in 40 of 42 recordings (cf. walking in which foot-strike always occurs with the heel first).

(2) *Adaptation in amplitude and timing of ground reaction force events to speed and mode of progression*

(a) *Stride cycle and support phase durations*

The duration of the stride cycle ( $T_c$ ) and support phase ( $T_{su}$ ) decreased progressively with speed in both walking and running (Fig. 3). The decrease in walking was more pronounced than in running. The support phase duration was longer than half the stride cycle duration at all speeds in walking and at the lowest running speed among the rearfoot strikers, indicating the

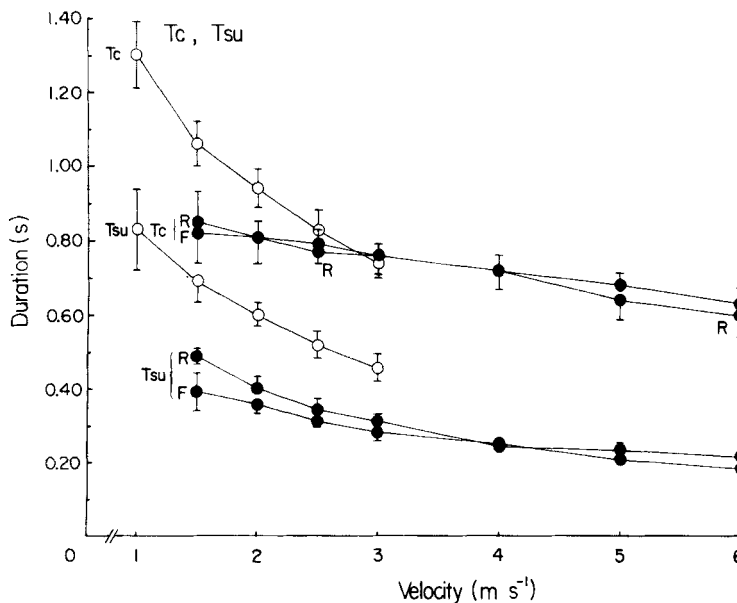


Fig. 3. Mean values ( $\pm 1$  SD) for stride cycle and support phase durations *vs* velocity of walking (○) and running (●). Stride cycle duration ( $T_c$ ) is defined as the time between one event in a cycle (here: onset of support phase of the right leg) and the same event in the following cycle. The support phase duration ( $T_{su}$ ) is defined as the time when one foot is in contact with the ground. R, rearfoot strikers; F, forefoot strikers.

presence of a double support phase, i.e. both feet in contact with the ground simultaneously. A transition from walking to running resulted in a shorter stride cycle duration (i.e. a higher stride frequency) at lower speeds and an approximately equal stride cycle duration at higher speeds. Note that the support phase (i.e. the time when the ground reaction forces occur) was always longer in walking as compared to running. Similar stride cycle durations were present for rear- and forefoot strikers during running. This was also true for the support phase duration except at low speeds. The absolute values in Figure 3 can be consulted in the interpretation of the timing data below, which are given in relation to normalized support phase durations.

#### (b) Timing of different events in the ground reaction forces

In Figure 4 the timing of peaks, troughs and transition events of the vertical, anteroposterior and mediolateral reaction force curves are plotted in relation to a normalized support phase (from touch down to toe off) at each speed tested.

**Walking.** Different types of adaptations to speed were seen in the timing of reaction force events in relation to the normalized support phase duration. Some events maintained a relatively constant phase relationship, whereas others showed phase-shifts with increasing speed. In the vertical ground reaction force curve the trough ( $F_{z2}$ ) and force peak at the end of the support phase ( $F_{z3}$ ) tended to occur later in the support phase with speed (particularly between 1.0 and 1.5 m s<sup>-1</sup>), whereas the contrary was true for the initial force peak ( $F_{z1}$ ). Of the anteroposterior force events, only the first small forward-directed force peak ( $F_{y1}$ ) showed a constant phase relationship. The braking ( $F_{y2}$ ) and the propulsive peaks ( $F_{y4}$ ) as well as the transition between these two ( $F_{y3}$ ) occurred earlier at higher speeds. The laterally directed force peak ( $F_{x1}$ ) in the beginning of the support phase showed a constant relative occurrence with speed, whereas  $F_{x2}$  had a less consistent pattern.

**Running.** Most reaction force events in running tended to occur relatively later in the normalized support phase with increasing speed. Note, however, that the largest differences often

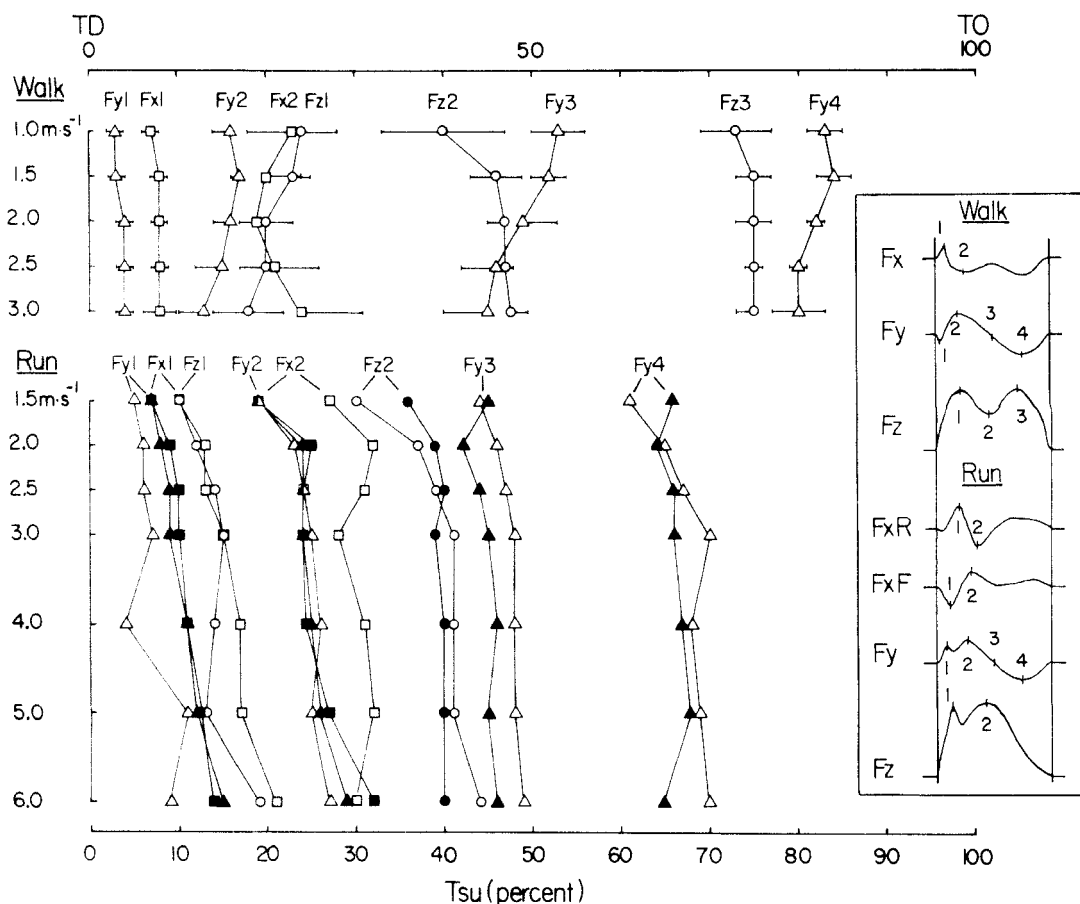


Fig. 4. Timing of different events in the vertical, anteroposterior and mediolateral reaction force curves (see Fig. 2) at different speeds of walking and running in relation to a normalized support phase duration (0–100% of  $T_{su}$ ). TD, touch-down; TO, toe-off. For definition of events and explanation of symbols see inset. R, rearfoot strikers; F, forefoot strikers. In running, rearfoot strikers have open symbols and forefoot strikers filled symbols. The standard deviations for the mean values in running are left out in the figure due to limited space. In running the mean standard deviations for the marked events of  $F_x$ ,  $F_y$  and  $F_z$  were 4.9, 2.7 and 3.4% respectively.

occurred at the low speeds. A striking difference in the occurrence of anteroposterior ( $F_y$ ) and mediolateral ( $F_z$ ) force peaks was present between rear- and forefoot strikers. The first and second anteroposterior and mediolateral force peaks ( $F_{y1}$  and  $F_{x1}$ ,  $F_{y2}$  and  $F_{x2}$ ) coincided at all speeds among the forefoot strikers but were clearly separated in time among the rearfoot strikers.

### (c) Ground reaction force amplitudes

**Vertical reaction force.** In walking the mean amplitude of the peak in vertical reaction force in

the beginning of the support phase ( $W_1$  in Fig. 5a) increased from 1.0 b.w. to 1.5 b.w. from the lowest to the highest speed. The other vertical force peak ( $W_3$ ) was approximately equal to the first peak at the lowest speeds but levelled off in amplitude at about 1.2 b.w. at higher speeds. The trough in the vertical force curve ( $W_2$ ) decreased progressively with speed from 0.9 b.w. to 0.4 b.w. at 2.5 m s<sup>-1</sup> (Fig. 5a). In running the vertical impact peak ( $R_1$ ) for rearfoot strikers increased linearly from 1.2 b.w. at 1.5 m s<sup>-1</sup> to approximately 2.6 b.w. at 6.0 m s<sup>-1</sup> (Fig. 5a). The main vertical peak ( $R_2$  for rearfoot and  $F_1$

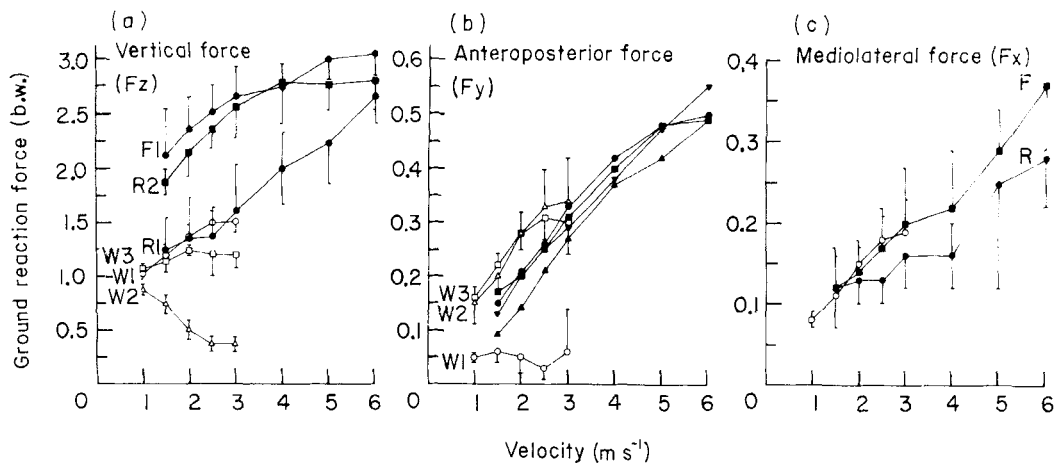


Fig. 5. Mean values ( $\pm 1$  SD) for selected amplitudes in ground reaction forces (see Fig. 2 and Fig. 4, inset) expressed in multiples of body weight (b.w.) vs velocity for walking (open symbols) and running (filled symbols). (a) Walk—W1 and W3 = first and second vertical reaction force peak, W2 = amplitude of the force in the trough in the vertical force curve; run—R1 = the initial vertical impact peak for rearfoot strikers, R2 and F1 = the main vertical peaks for rearfoot and forefoot strikers respectively. (b) Walk—W1 = the small initial propulsive force peak, W2 and W3 = braking and propulsive peak forces respectively; run—braking peak force among rearfoot (●) and forefoot (■) strikers, propulsive peak force among rearfoot (▲) and forefoot (▼) strikers. The values for the mediolateral forces (c) are peak-to-peak values. The standard deviations of the anteroposterior mean braking and propulsive forces in running (b) are left out due to limited space. The mean standard deviations of these forces for the fore- and rearfoot strikers were 0.06 and 0.05 b.w. respectively. R, rearfoot strikers, F, forefoot strikers.

for forefoot strikers) increased with speed from approximately 2.0 b.w. to about 2.9 b.w. at 5–6 m s<sup>-1</sup> (Fig. 5a).

**Anteroposterior reaction force.** The braking and propulsive peak forces in walking (W2 and W3 in Fig. 5b) increased from approximately 0.15 b.w. at 1.0 m s<sup>-1</sup> to 0.3 b.w. at 2.5–3.0 m s<sup>-1</sup>. The initial peak (W1) corresponded only to approximately 0.05 b.w. and did not change consistently with speed. In running the peaks in braking and propulsive reaction forces increased linearly from about 0.13 b.w. at the lowest speed to about 0.5 b.w. at the highest speed (Fig. 5b). No systematic differences in anteroposterior peak force amplitudes were seen between the rear- and forefoot strikers.

**Mediolateral reaction force.** The peak-to-peak mediolateral force increased with speed in walking (Fig. 5c) from 0.08 b.w. at the lowest speed to 0.19 b.w. at the highest speed. In running the peak-to-peak mediolateral force increased from 0.12 b.w. to 0.28 b.w. for rearfoot

and to 0.37 b.w. for forefoot strikers (Fig. 5c). The forefoot strikers showed higher peak-to-peak mediolateral forces than the rearfoot strikers, except at the lowest speeds. Forefoot strikers had approximately the same values in running as in walking (with heel-strike) at comparable speeds.

#### (d) Ground reaction impulses

**Vertical impulse.** In walking the total vertical impulse (the area under the force–time curve) decreased with speed from 500 to 290 N s (Fig. 6a). In running the total vertical impulse values also decreased and there was no significant difference between the rear- and forefoot strikers in this respect. The mean values were approximately 330 N s at 1.5 m s<sup>-1</sup> and 240 N s at the highest speed. At lower comparable speeds the total vertical impulse was significantly larger in walking as compared to running, but at higher speeds they were approximately equal (Fig. 6a).

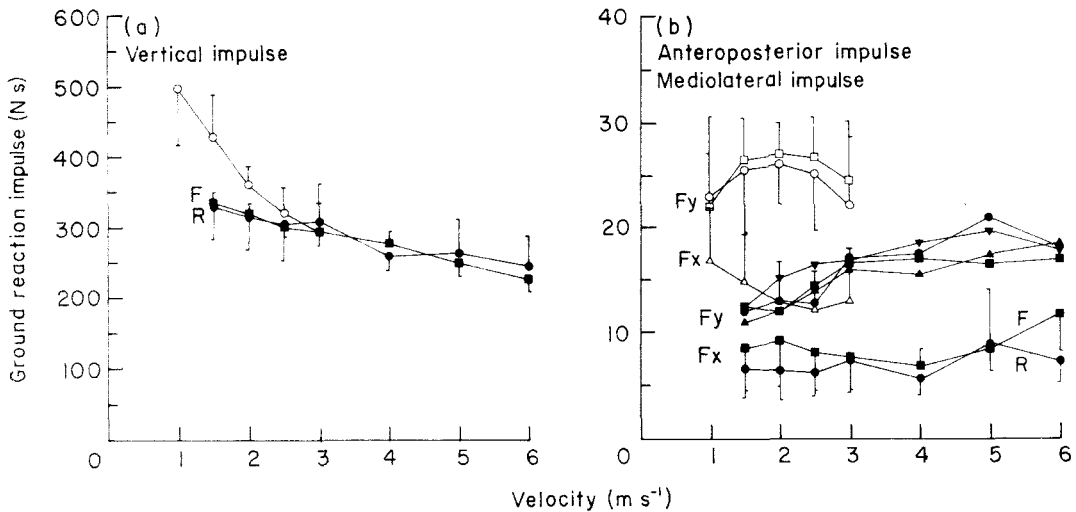


Fig. 6. Mean values ( $\pm 1$  SD) for ground reaction impulses (N s) vs speed of walking (open symbols) and running (filled symbols). R, rearfoot strikers; F, forefoot strikers. (a) Total vertical impulse. (b) Anteroposterior and mediolateral impulses. Walk— $F_y$ , braking ( $\circ$ ) and propulsive ( $\square$ ) impulses;  $F_x$ , total impulse ( $\triangle$ ). Run— $F_y$ , braking impulses of rearfoot ( $\bullet$ ) and forefoot ( $\blacksquare$ ) strikers, propulsive impulses of rearfoot ( $\blacktriangle$ ) and forefoot ( $\blacktriangledown$ ) strikers. The standard deviations of the anteroposterior braking and propulsive mean impulses in running (b) are left out due to limited space. The mean standard deviations of these impulses for the fore- and rearfoot strikers were 2.8 and 3.2 N s respectively.

**Anteroposterior impulse.** In walking the braking and propulsive impulses showed an inverted U-shaped relation to velocity (Fig. 6b). At higher speeds the propulsive impulse was somewhat higher than the braking impulse and reached its maximal value of 27 N s at 2.0 m s<sup>-1</sup>. In running the braking and propulsive anteroposterior impulses were approximately equal at all speeds (Fig. 6b). No systematic difference could be seen between the two foot-strike types. The anteroposterior impulses increased from approximately 12 N s at 1.5 m s<sup>-1</sup> to about 18 N s at 6.0 m s<sup>-1</sup>. A transition from walking to running resulted in a markedly lower anteroposterior impulse (Fig. 6b).

**Mediolateral impulse.** In walking the total mediolateral impulse decreased with speed from 17 to 13 N s (Fig. 6b). In running this impulse was approximately 8 N s and showed no systematic change with speed. Similar values were seen among the rear- and forefoot strikers. Running showed clearly lower mediolateral impulses than walking at the same speeds (Fig. 6b).

## DISCUSSION

### Speed adaptation

The results presented here on overground locomotion are in agreement with data from earlier studies on walking and running on a motor-driven treadmill over a wide range of velocities (Grillner *et al.* 1979, Thorstensson *et al.* 1984, Nilsson *et al.* 1985a). In this study, as in most previous ones, speed adaptation in human locomotion has been investigated by comparing performance characteristics at different constant speeds (cf., however, Thorstensson & Roberthson 1987). Naturally, the reaction force pattern, particularly in the anteroposterior direction, will be quite different in this situation as compared to that during acceleration and deceleration. Theoretically, one prerequisite for maintaining a constant speed of progression is that the decelerating and accelerating horizontal impulses are equal, which means that no net change occurs in body momentum in the anteroposterior direction. In practice, a small

difference could be expected, with the accelerative impulse being somewhat larger to overcome, for example, air resistance, especially at higher speeds. Our results showed approximately equal accelerative and decelerative anteroposterior impulses both in walking and running. Any systematic differences in impulse related to, for example, air resistance could be hidden in the small variation in speed (about 4%), which was unavoidable with the present experimental design, even though great care was taken to keep the speed constant (see Methods).

Differences in speed adaptation of the anteroposterior impulses were seen between walking and running. In running there was a monotonous increase in braking impulse (Fig. 6b) which could be related to the increased distance of foot placement in front of the body (Nilsson *et al.* 1985a). This reasoning can also be applied to explain (at least part of) the increase in anteroposterior impulse at lower speeds in walking and, as a matter of fact, even to account for some of the decrease in braking impulse at higher walking speeds, since the foot then is placed closer to the body at foot-strike (Nilsson *et al.* 1985a). In addition, the double support phase duration also decreases with speed (Nilsson & Thorstensson 1987), which reduces the need to counteract the braking impulse of the contralateral leg (these forces could not be measured here since only one force-plate was available).

With increasing speed there were similar adaptations of the vertical peak force amplitudes for both walking and running. In both cases a tendency to level off was present after an initial increase at lower speeds (Fig. 5a). Due to the continuous contact with ground in walking the mean amplitude of the vertical force has to be approximately equal to body weight. Thus, the trough between the two peaks in walking became progressively larger with speed. In running, on the other hand, the body travels forward via single support phases interrupted by airborne phases. The height of each airborne phase will be related to the size of the resultant vertical impulse (see Munro *et al.* 1987).

#### *Walking and running at the same speeds*

A comparison of the reaction force parameters in walking and running at the same speeds shows basic similarities as well as some striking differences. Similar results have been demon-

strated also for movement and muscle activity patterns. (Thorstensson *et al.* 1982, 1984, Nilsson *et al.* 1985a), indicating at least partly different motor programmes and mechanical solutions for progression in human walking and running.

There were conspicuous differences in the anteroposterior impulses between walking and running at the same speeds. Both braking and accelerating impulses were clearly larger in walking (Fig. 6b). This difference can be related to the existence of a double support phase in walking, and also to a lower stride frequency and to other differences in movement patterns, such as the placement of the foot further in front of the body at touch-down in walking as compared to running (Nilsson *et al.* 1985a).

The typical differences between walking and running in the vertical force-time curves are coupled to fundamentally different paths of the centre of gravity of the body during the support phase. In walking the centre of gravity is elevated during single support and reaches its peak height approximately at mid-support. The trough in the vertical force curve should roughly coincide with this position, since deceleration upwards followed by acceleration downwards causes an unloading of the ground. In running, the situation is reversed, since the centre of gravity reaches its lowest position at approximately mid-support. In both modes of progression the lowest forward velocity (i.e. the lowest kinetic energy) occurs after the braking impulse (approximately at mid-support). This means that there is a possibility to utilize a transfer between potential and kinetic energy in walking, but not in running (Cavagna *et al.* 1963, Cavagna & Margaria 1964, Margaria 1976). Comparing the timing of the force events in Figure 4 it can be seen that a phase relationship which allows for energy transformation exists for walking ( $F_{z2}$  vs  $F_{y3}$ ). At lower speeds there was a time-lag, which may indicate a lesser efficiency from an energetic point of view. In running, on the other hand, the minimal potential and kinetic energy (represented by  $F_{z2}$  and  $F_{y3}$  in Fig. 4) occur rather close in time and therefore exclude such energy transformation.

A transition from walking to running also resulted in an abrupt decrease in total medio-lateral impulse (Fig. 6b). This could be related to the smaller body movements in the frontal plane (Thorstensson *et al.* 1984) and the placement of the foot closer to the midline in

running (Cavanagh 1987). In walking the occurrence of double support means that the feet have to be placed further away from the midline.

### *Foot-strike patterns in running*

Foot-strike pattern during running varies from individual to individual (Cavanagh & LaFortune 1980, Cavanagh 1987). It is of interest to investigate how these differences in movement patterns are reflected in reaction force parameters, which in turn may be related to, for example, energy cost and injury-proneness. In our results, basic similarities in the general reaction force patterns were seen between rear- and forefoot strikers. However, some differences were present both in the shape of the force curves and in the timing and amplitude of different force events. The rearfoot strikers showed an initial vertical impact peak (Fig. 2) which was absent or diminished among the forefoot strikers. These results are in line with earlier findings on rear- and midfoot strikers (e.g. Cavanagh & LaFortune 1980, Clarke *et al.* 1983, Munro *et al.* 1987). The landing on the anterior part of the foot implies that there has to be a higher force transmitted through the Achilles tendon at impact in forefoot strikers. The possible importance of this difference in, for example, the aetiology of running injuries needs to be further elucidated.

The anteroposterior braking force curve showed, particularly among the forefoot strikers, two clearly separated peaks, and the trough between the peaks sometimes reached zero force. The origin of these peaks is at present unclear. It has been indicated that their appearance correlates with the migration of the centre of pressure under the foot during support (Cavanagh 1987). In the mediolateral force the direction of the first peak differed between rear- and forefoot strikers in running. The rearfoot strike resulted in a laterally directed reaction force peak similar to walking, in which the rear part (heel) of the foot also strikes ground first. An interesting finding was the difference in temporal relationship of the peaks in the mediolateral and anteroposterior force depending on type of foot-strike. In the forefoot strike these two peaks occurred almost simultaneously, whereas there was a phase-shift between the peaks among the rearfoot strikers. This difference was consistent at all speeds. The functional

meaning of these differences in timing of force events needs further studies, combining kinematic and kinetic analysis, to be fully understood.

There is a complex interaction between vertical and horizontal reaction force components to provide the forces necessary for propulsion and equilibrium control during human locomotion. Marked differences in some force parameters were demonstrated between walking and running, particularly in the shape and amplitude of the vertical force, which are a consequence of fundamental differences in movement strategies between the two major forms of human progression. A transition from walking to running, which normally occurs at a speed of about  $2 \text{ m s}^{-1}$  (Thorstensson & Roberthson 1987), would result in lower impulses during each foot contact, but also in a higher number of foot contacts per unit of time. Certain differences in the shape, timing and amplitude of the reaction forces were also demonstrated within the running form of locomotion depending on type of foot-strike. The functional implications of these differences, as well as the reasons why a certain individual exhibits one type of foot-strike or the other, are still obscure. On-going studies will attempt to elucidate these questions from an energetic and motor control point of view.

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