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THE INFLUENCE OF RUNNING VELOCITY AND MIDSOLE HARDNESS ON EXTERNAL IMPACT FORCES IN HEEL–TOE RUNNING

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Abstract—The purpose of this study was to investigate the influence of midsole hardness and running velocity on external impact forces in heel–toe running. Fourteen subjects were assessed with a force platform and high speed film while running at speeds of 3, 4, 5 and 6 m s^{-1}. The result showed that running velocity does influence external impact force peaks (linear connection) and that midsole hardness does not influence magnitude and loading rate of the external vertical impact forces. Changes in kinematic and kinetic data can be used to explain this result mechanically. However, the neuromuscular control mechanisms to keep external impact forces constant are not known.

INTRODUCTION

Ground reaction forces acting on a runner's foot during each foot contact can be subdivided into an initial part during which the segments close to the ground are decelerated followed by a second part which describes the mid stance and push off phase. The first part of these force curves is discussed in the literature as passive force peaks (Nigg and Denoth, 1980; Nigg and Luethi, 1980), as initial peaks (Cavanagh and Lajortune, 1980) or as impact force peaks (Frederick *et al.*, 1981; Clarke *et al.*, 1983a; Nigg, 1983). An impact force peak (the expression used in the following for this force peak) for heel–toe running is defined as the vertical force peak which occurs within the first 50 m after touchdown of the heel on the ground.

One reason why impact forces are studied is the assumption that there is a connection between 'shoe cushioning' and impact forces. It is assumed that impact forces can be influenced by altering the material properties of the midsole under the heel (Cavanagh, 1980; Rodano, 1983; Bojsen-Møller, 1983). Furthermore, it is generally assumed that the impact force peaks are connected with the occurrence of pain and injuries in running (Hess and Hort, 1973; Hort, 1976; James *et al.*, 1978; Clement *et al.*, 1981; Segesser and Stacoff, 1981). High impact forces have been speculated to cause damage to articular cartilage (Puhl, 1980; Thiel, 1980). This speculation is supported by findings from Radin and co-workers (1973) who showed that large impact forces can produce degenerative changes in cartilage. The same group showed (Radin *et al.*, 1982) a change in differences of biochemical and mechanical characteristics of knee cartilage of sheep for a group walking on asphalt compared to a group walking on compliant wood chips. Falsetti and co-workers (1983) could show hematological differences between endurance running with soft and hard soled running shoes.

Periodic stretching of soft tissue with high loading rates due to impact forces is assumed to be connected with pain and injuries in the lower leg. If, at impact, the point of application of the ground reaction force in heel–toe running is on the posterior side of the ankle joint and the lateral side of the subtalar joint, high external moments around these joints may be produced which may cause injuries in the medial anterior part of the tibia. Problems at the origin of the tibialis anterior, for instance, could be connected with impact moments producing a fast plantar flexion and eversion of the foot and therefore a high loading rate at its origin. This stretching can also produce microtraumas in the bone which can lead to fatigue fractures if the recovery time is too short (Krahl and Steinbrueck, 1980).

Impact forces are important variables which must be studied to understand the etiology of some running injuries. They may be influenced by external factors (boundary conditions) such as velocity of running, midsole hardness, body weight, surface hardness and others.

The purpose of this study is to investigate the influence of midsole hardness and running velocity on the external impact forces for heel–toe running. The knowledge of the influence of these two external factors on impact forces provides one further step in the understanding of cushioning properties of running shoes.

MATERIALS AND METHODS

Fourteen male runners with a mean mass of 73 kg (S.D. $\pm$ 6 kg) volunteered to participate in this study. Seven of them were recreational and seven were competitive runners. Three pairs of shoes (size 9) were used in the study. They were identical in construction except in the material properties of the midsole. The hardness, quantified with a method measuring the

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resistance of the material against penetration (Shore A measurement), was systematically varied (25, 35 and 45 Shore). The subjects had to run over a force platform (Kistler, Type Z4852/C) with a natural frequency of at least 250 Hz in all three channels. The runway was about 16 m with the force platform located in the middle of it. Each subject performed as many practice runs as needed to land consistently on the force platform with the right foot. The measurements were performed with four different running velocities (3, 4, 5 and $6\ \mathrm{m\,s^{-1}} \pm 0.2\ \mathrm{m\,s^{-1}}$) and three different shoe hardness conditions. The average running velocity was controlled by photocells which were mounted 1.56 m from the centre of the force platform in both directions at hip height. Each subject had to perform a total of twelve trials with contact on the force platform and the prescribed velocities. Trials where the running velocity was outside the prescribed range or where the foot was outside the force platform area were discarded. The sampling rate for the force measurement was 1020 Hz for each channel. Simultaneous film measurements were taken from posterior and lateral views with a film frequency of 200 frames per second. Data analysis was performed as described elsewhere (Nigg, 1986).

The main variables discussed in this context are the maximal impact force peak in the vertical direction, F_{zi}, the time of occurrence of this peak after initial contact, t_{zi}, the maximal loading rate, G_{zi}, of the vertical force, the time of occurrence, t_{Gi}, of this maximal loading rate and the maximal active force peak, F_{za}. In addition the angle of the lower leg (posterior view), α_0, the rearfoot angle, γ_0, the angle between shoe sole and the horizontal (sole angle), δ_0, the knee angle at the posterior side, ε_0, and the landing velocity of the heel in vertical and a–p direction, v_{0z} and v_{0y}, all immediately before ground contact were determined as described by Nigg (1986).

A one-way analysis of variance with a multiple range test (Tukey-B procedure) was used for the statistical analysis. The level of significance was chosen to be $\alpha = 0.05$.

RESULTS

Results with respect to the influence of the velocity and the influence of the midsole hardness are reported. A summary of the results is listed in the Appendix (Tables 1–4).

Influence of the velocity

The influence of the change of velocity from $3\ \mathrm{m\,s^{-1}}$ to $6\ \mathrm{m\,s^{-1}}$ in steps of $1\ \mathrm{m\,s^{-1}}$ on the force variation is shown in Fig. 1 for all shoe conditions. The mean values of the impact force peaks, F_{zi}, increase from 1.33 kN for $3\ \mathrm{m\,s^{-1}}$ to 2.17 kN for $6\ \mathrm{m\,s^{-1}}$. The increase is relatively constant so that for the investigated interval of running velocities between 3 and $6\ \mathrm{m\,s^{-1}}$ the connection between velocity and impact force peak can be assumed to be linear. However, the extrapolation of an assumed linear regression line does

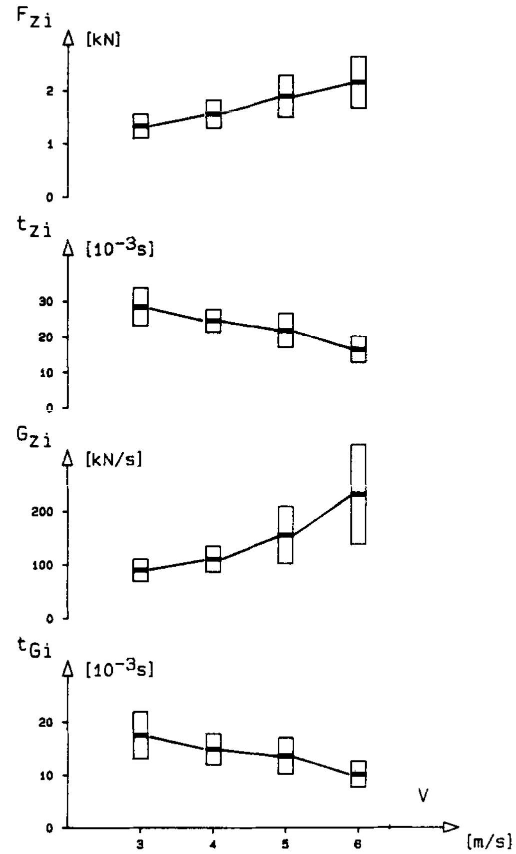


Fig. 1. Influence of running velocity, v, on the vertical impact force peak, F_{zi}, its time of occurrence, t_{zi}, the maximal vertical loading rate, G_{zi}, and its time of occurrence, t_{Gi}, (mean and S.D.).

not pass through the origin but has a residual impact force of about 500 N for an assumed velocity of $0\ \mathrm{m\,s^{-1}}$. The time of occurrence, t_{zi}, of the impact force peak decreases with increasing running velocity from 28.4×10^{-3} s for $3\ \mathrm{m\,s^{-1}}$ to 16.6×10^{-3} s for $6\ \mathrm{m\,s^{-1}}$. The decrease in this range of running velocities is fairly linear.

The maximal slope, G_{zi}, increases from $90.0\ \mathrm{kN\,s^{-1}}$ for $3\ \mathrm{m\,s^{-1}}$ to $232.8\ \mathrm{kN\,s^{-1}}$ for $6\ \mathrm{m\,s^{-1}}$ running velocity. The increase in the maximal slope values is not linear. An extrapolation of an assumed quadratic relationship between the maximal slope G_{zi} and the running velocity leaves a residual maximal loading rate of about $50\ \mathrm{kN\,s^{-1}}$. The time of occurrence of the maximum loading rate, t_{Gi}, decreases with increasing running velocity. The decrease in this interval of running velocity is similar to the decrease for t_{zi} and is assumed to be linear in the studied interval.

The results for the active force peaks (Fig. 2) show a significant increase from 1.86 kN for $3\ \mathrm{m\,s^{-1}}$ to 2.26 kN for $6\ \mathrm{m\,s^{-1}}$ running velocity.

The initial conditions show some changes for the different running velocities. The vertical component of the landing velocity, v_{0z}, increases significantly from $0.8\ \mathrm{m\,s^{-1}}$ for $3\ \mathrm{m\,s^{-1}}$ to $1.9\ \mathrm{m\,s^{-1}}$ for $6\ \mathrm{m\,s^{-1}}$ (Fig. 3). However, the anterior–posterior component, v_{0y}, does

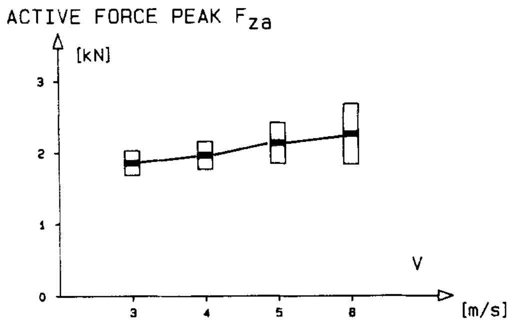


Fig. 2. Influence of running velocity, v_i, on the active vertical force peak, F_{za} (mean and S.D.).

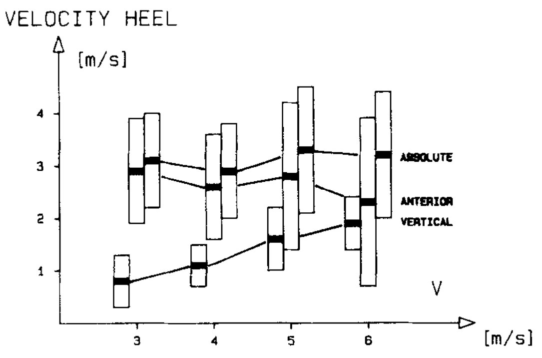


Fig. 3. Influence of running velocity, v, on the touch down velocity of the heel (mean and S.D.).

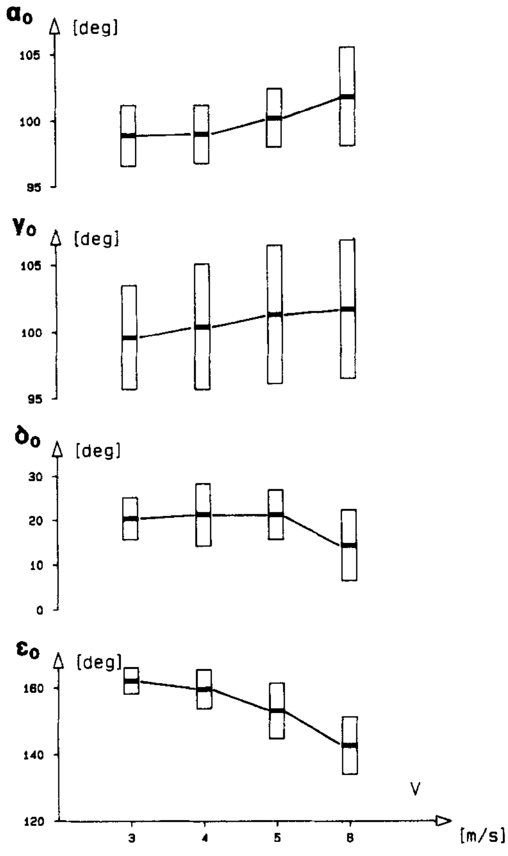


Fig. 4. Influence of running velocity, v, on the initial position of the lower leg, α_0, the rearfoot, γ_0, the shoe sole, δ_0, and the knee, ε_0 (mean and S.D.).

not show a significant difference. Similarly the total velocity of touch down of the heel, which is dominated by the a–p component, does not show a significant difference for changing running velocity.

The geometric position of the lower extremities immediately before landing is described by the angle of the lower leg, α_0, the rearfoot angle, γ_0, the shoe sole angle, δ_0, and the knee angle ε_0. The results for the mean values for all shoes for the four different running velocities are illustrated in Fig. 4. The angle of the lower leg immediately before contact, α_0, increases slightly from 98.9° to 101.8° for increasing running velocities from 3 to 6 m s^{-1}. The rearfoot angle immediately before contact, γ_0, shows the same tendency in the mean values increasing from 99.6 to 101.7° for increasing running velocities from 3 to 6 m s^{-1}. The angle of the shoe sole immediately before touch down, δ_0, is relatively constant for the three slower running velocities (between 20.4° and 21.3°) with no significant differences for this range of running velocities. It decreases to 14.4° for the fastest running velocity (6 m s^{-1}) and this value differs from the others significantly. The subjects, therefore, place the foot in a flatter a–p position for the fastest running velocity. The values of the knee angle immediately before touch down, ε_0, decrease from 162.2° for 3 m s^{-1} to 142.7° for 6 m s^{-1}. The differences between 4, 5 and 6 m s^{-1} are significant. The subjects bend their knees more before landing with their heel with increasing velocities. The strategy of using reduced knee angles for faster velocities is used consistently by all subjects.

Influence of the midsole hardness

Figure 5 shows the effect of midsole hardness on the magnitude of the impact force peaks. It shows a slight decrease of less than 10% of the maximum impact forces for increasing shore values (harder midsole materials) in six of the eight intervals but this decrease is not significant. The time of occurrence, t_{zi}, of the impact force peak with changing midsole hardness remains constant in changing from shore 25 to shore 35 and tends to decrease (significant for 3 m s^{-1} and 5 m s^{-1}) in changing from shore 35 to shore 45.

The maximum slope, G_{zi}, remains constant in the studied range of midsole hardnesses (Fig. 6). The differences for one running velocity are smaller than 15% between the lowest and the highest values and are not significant. The time of occurrence, t_{Gi}, of the maximum loading rate remains constant between midsole hardnesses of 25 and 35 shore. It decreases between midsole hardnesses 35 and 45 shore (significant for 4, 5 and 6 m s^{-1}) with an average decrease of about 35%.

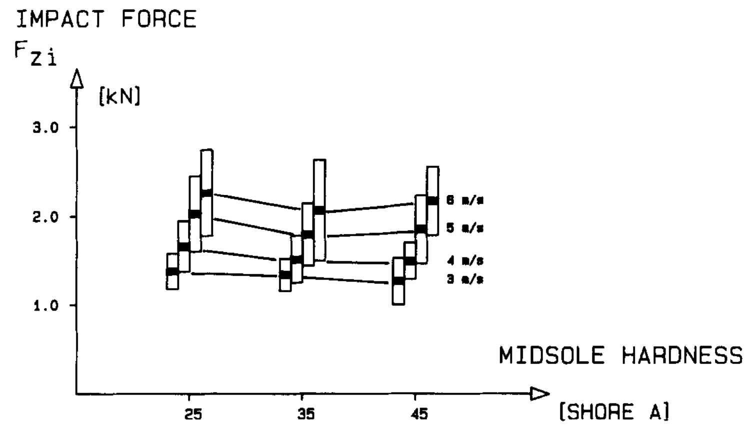


Fig. 5. Influence of midsole hardness on the vertical impact force peak, F_{zi}, for various running velocities (mean and S.D.).

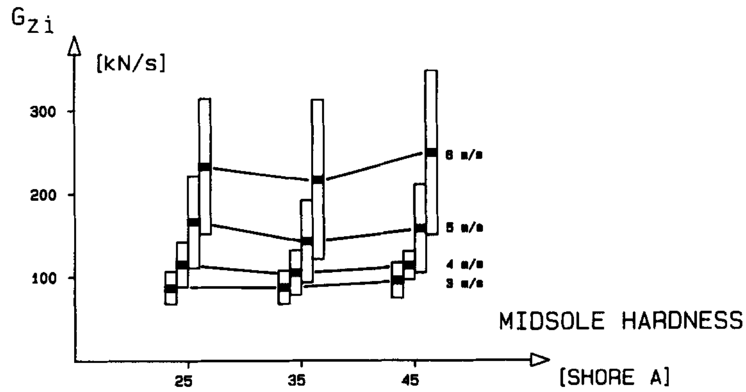


Fig. 6. Influence of midsole hardness on the maximal vertical loading rate, G_{zi}, for various running velocities (mean and S.D.).

The influence of the midsole hardness on the initial conditions described by the touchdown velocity and the angles of the knee, the lower leg, the shoe sole and the rearfoot are illustrated in Figs 7 and 8. The two graphs illustrate that these variables (the absolute velocity of the heel; their horizontal and vertical component; the angle of the lower leg, α_0; the rear-foot angle, γ_0; the shoe sole angle, δ_0; and the knee angle, ε_0 all measured immediately before touch down) do not show a difference for changing midsole hardnesses in the studied range.

DISCUSSION

Impact forces and running velocity

The result that vertical impact force peaks increased with increasing running velocity may have been expected. A similar result has been reported earlier (Frederick *et al.*, 1981) based on a study with nine runners for a smaller velocity range (3.4–4.5 m s^{-1}). Their results indicated a linear increase of the vertical impact force peaks with increasing running velocity. A comparison between the results of the present study with the results of the previous study (Frederick *et al.*, 1981) shows different coefficients for the linear term in a linear regression equation and different vertical impact force peaks at zero velocity (coefficients for forces in kN and velocities in m s^{-1})

Frederick (1981) $F_{zi} = 0.54v - 0.45$
Nigg (1987) $F_{zi} = 0.29v + 0.48.$

The vertical impact force peaks increase more with increasing running velocity using Frederick's results compared to estimations based on the results of the present study. This difference may be connected with footwear, running style or other factors.

An extrapolation of the experimentally determined linear relationship to running velocities below the velocities used during the experiment allows the prediction of residual vertical impact force peaks at zero running velocity. Using Frederick's results, the residual vertical impact force peak is -450 N. Using the results of the present study the residual vertical impact force peak is $+480$ N. A negative vertical impact force has no physical meaning and cannot be explained. The

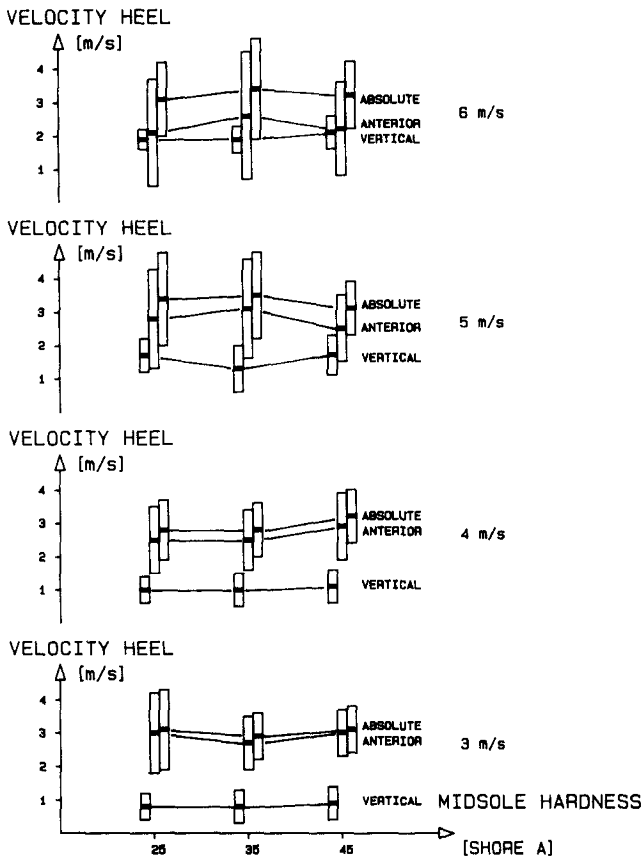


Fig. 7. Influence of midsole hardness on the touch down velocity for various running velocities (mean and S.D.).

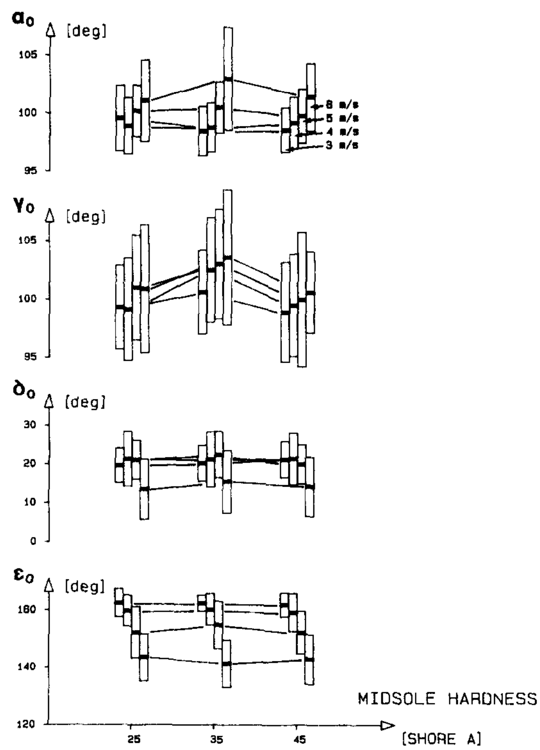


Fig. 8. Influence of midsole hardness on the initial position of the lower leg, α_0, the rearfoot, γ_0, the shoe sole, δ_0 and the knee, ε_0 for various running velocities (mean and S.D.).

result of a positive residual impact force peak could be explained with contact forces during running at one spot.

For running velocities between 3 and $6\,\mathrm{m\,s^{-1}}$, the vertical impact force peaks increased only 63% compared to 130% of the vertical touch down velocities. This can be explained using the kinematic and kinetic results determined experimentally. The decrease of the knee angle at touch down, ε_0, with increasing running velocity indicates a reduced mass experiencing high deceleration during the initial phase of contact. This is connected with a decreased vertical impact force peak (Denoth, 1986). Furthermore, the time between first contact and vertical impact force peak decreased with increasing running velocity. This is connected with a decrease in the mass experiencing high deceleration in the initial phase of contact which again corresponds to a decrease in the vertical impact force peak. The impact forces could also be influenced by the stiffness of the shoe–foot system. The material aspects of it were kept constant for all running velocities. The geometrical aspects (landing on an edge is softer than landing on a flat sole) were checked with the initial sole angle, δ_0, and the initial rearfoot angle, γ_0. The initial rearfoot angle had a slight increase, the initial sole angle a slight decrease comparing the results for 3 and $6\,\mathrm{m\,s^{-1}}$. These changes affect the spring stiffness of the sole–foot system but cancel each other.

The experimental result that impact forces increase less than vertical touch down velocities of the heel with increasing running velocity can, therefore, be qualitatively explained with the changes in the magnitude of temporal and kinematic variables. The idea used for this explanation that the mass involved in the initial deceleration process changes with changing position of the leg and changing signal frequency of the input signal (force) is described in the effective mass model (Denoth, 1986).

Impact forces and midsole hardness

A change in midsole hardness from shore 24 to shore 45 did not change the vertical impact force peaks significantly for all four running velocities. This result agrees with findings reported in the literature for one running velocity (Nigg *et al.*, 1983; Clarke *et al.*, 1983b; Kaelin *et al.*, 1985). There are two aspects which seem to be important to explain this result. Describing surface, shoe and heel pad as a system of three springs one would expect a significant change in impact force peaks due to the changed spring stiffness of the shoe sole assuming that the surface stiffness is highest and that the stiffness of the shoe sole and the stiffness of the heel pad are in the same order of magnitude (Nigg and Denoth, 1980). The maximum impact force, F_{zi}, in a simple spring-mass model depends on the spring stiffness f and the kinetic energy E_{kin}

$$E_{kin} = \tfrac{1}{2} f \Delta z^2$$
$$\Delta z = \text{deformation};$$
$$F_{zi} = f \Delta z$$
$$E_{kin} = \frac{1}{2}\frac{1}{f} F_{zi}^2$$
$$F_{zi} = \sqrt{2 f E_{kin}}.$$

The experimental results suggest that the kinetic energy was fairly constant (no differences in vertical touch-down velocities and geometrical position of foot and leg at touch down for each individual running velocity). One would, therefore, expect the vertical impact force peaks to increase quadratically with linearly increasing mid-sole stiffness.

A comparison of the film data shows a difference in the foot movement in the first few milliseconds. The point of application at initial contact was more on the lateral side of the shoe for the harder midsole (Fig. 9). The distance of this force to the subtalar joint axis is, therefore, bigger for the shoe with the harder midsole than for the shoe with the softer midsole (shore 25). The forces produce a bigger moment with respect to the subtalar joint axis for the harder shoe than for the softer shoe which results in a higher initial pronation and a higher initial pronation velocity. This is supported by experimental data. The average initial pronation velocity of the rear foot, $\dot{\gamma}_{10}$, is 9.7 degrees s^{-1} for the midsole with shore 25, 18.3 degrees s^{-1} for the midsole with shore 35 and 22.2 degrees s^{-1} for the midsole with shore 45. This increased initial pronation velocity corresponds to an increased deceleration distance in a given time interval which corresponds to a decreased initial force.

The increase of the hardness of the midsole and the change in the initial movement pattern produce changes in the vertical impact force peaks which are opposite in direction. Since the experimental result did not show a difference in the vertical impact force peaks for the different midsole hardnesses between 25 and 45 shore, it can be assumed that the two effects are of similar order of magnitude. It is not known at this time whether this increased initial pronation is imposed solely by mechanical reasons (different lever arm between force and subtalar joint axis) or whether it is a combined result of external mechanical changes and internal adaptation of the neuromuscular control system.

CONCLUSION

The experimental results of this study illustrate that increasing running velocity increases impact forces and impact loading rate. One strategy for a runner to reduce impact forces is therefore to reduce running speed. However, this strategy to reduce impact forces will most likely not be applied since most runners select their speed to achieve an appropriate stress of the cardiovascular system.

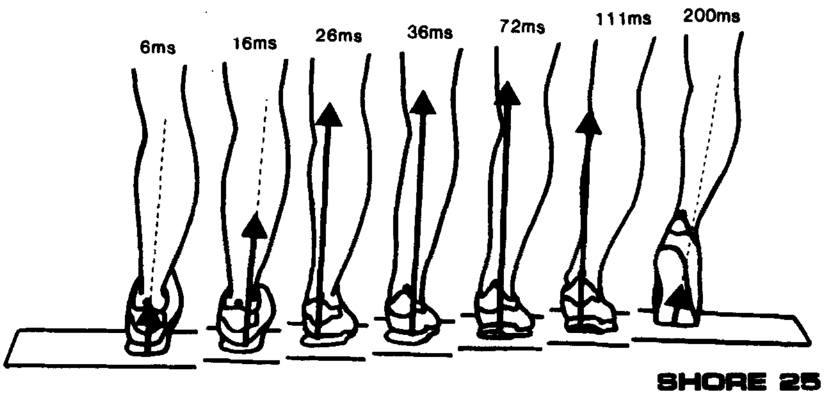
The second result, that external vertical impact force peaks do not change with changing midsole hardness, as long as the sole does not bottom out, is certainly surprising. 'Common sense' would expect smaller impact force peaks for softer midsole materials. However, the human subject obviously reacts on the change in midsole hardness. The strategy chosen by the tested runners was to keep the external impact force peaks constant. There are various possibilities to speculate about these results. One could propose that this result is connected with a protection mechanism assuming that the external input into the system is kept constant for given boundary conditions. Another speculation could be that the shoe changes the external sensation of load in the foot, concentrating on external instead of internal load. The fact that external and internal impact forces are not identical but depend on the lever arms of the acting forces with respect to joint axes makes an attempt of an interpretation even more difficult. The reason for this behaviour is certainly not known yet and more research is needed to answer this question.

The conclusions from this experiment are that changes in midsole hardness

(a) do not change impact force peaks, and

(b) do change the location of the point of application of the acting external ground reaction force relative to the foot.

A change of midsole hardness is therefore not responsible for 'better cushioning'. It changes the effect of the external force on internal structures. The initial ground reaction force for the softer midsole has a smaller lever arm with respect to the subtalar joint than



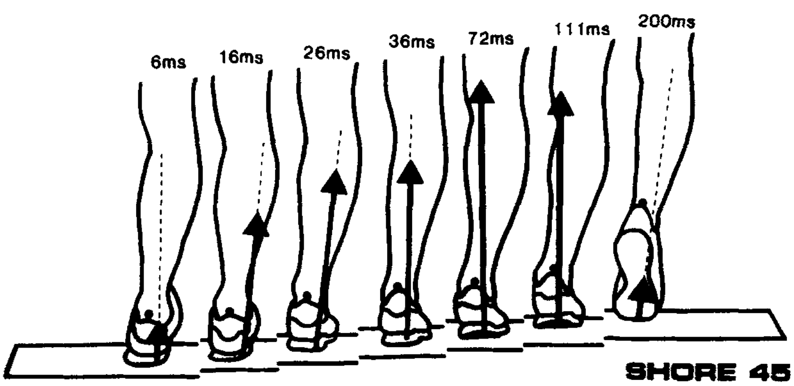


Fig. 9. Effect of soft and hard midsole materials on the external ground reaction force with respect to the athlete's leg. Example for one subject running with a soft midsole (shore 25) and a hard midsole (shore 45) with a running velocity of $4\,m\,s^{-1}$.

the harder midsole. Dynamic estimations (Denoth, 1986) show that the joint is more loaded with softer midsole and the medial ankle joint structures (e.g. tendon of tibialis posterior, tendon of hallucis longus) are more loaded with the harder midsole. A change in midsole hardness is therefore responsible for a redistribution of load. The common assumption that the hardness of the midsole can be used to reduce external impact forces ('cushioning') is not correct.

The purpose of this project was to study the influence of midsole hardness and running velocity on impact force peaks. The result is that running velocity does influence the external impact force peaks (linear connection) and that midsole hardness does not influence them at all. The result also suggests that different cushioning materials in the midsole can be used to influence the internal impact forces. Softer midsole materials reduce ligamentous forces and increase joint forces. Harder midsole materials increase ligamentous forces and decrease joint forces if nothing else is changed.

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APPENDIX

Table 1. Summary of the variables of interest grouped by running velocity (mean and S.D.)

		$3\,\mathrm{m\,s^{-1}}$	$4\,\mathrm{m\,s^{-1}}$	$5\,\mathrm{m\,s^{-1}}$	$6\,\mathrm{m\,s^{-1}}$
N		42	42	42	42
T	10^{-3} s	286.0	241.2	209.6	182.8*
		(22.3)	(19.3)	(16.5)	(12.0)
F_{zi}	kN	1.331	1.561	1.896	2.170*
		(0.225)	(0.267)	(0.400)	(0.489)
t_{zi}	10^{-3} s	28.4	24.6	21.8	16.6*
		(5.3)	(3.2)	(4.8)	(3.7)
G_{zi}	kN s^{-1}	90.0	111.3	155.7	232.8*
		(20.9)	(24.4)	(53.6)	(93.1)
t_{Gi}	10^{-3} s	17.5	14.9	13.6	10.2*
		(4.4)	(2.9)	(3.4)	(2.5)
F_{za}	kN	1.860	1.970	2.138	2.263*
		(0.171)	(0.194)	(0.285)	(0.423)
α_o	degrees	98.9	99.0	100.2	101.8*
		(2.3)	(2.2)	(2.2)	(3.7)
γ_o	degrees	99.6	100.4	101.3	101.7*
		(3.9)	(4.7)	(5.2)	(5.2)
δ_o	degrees	20.4	21.3	21.2	14.4*
		(4.7)	(7.0)	(5.5)	(7.9)
ε_o	degrees	162.2	159.7	153.1	142.7*
		(3.9)	(5.8)	(8.3)	(8.5)
$\Delta\gamma_{10}$	degrees	−4.5	−4.9	−7.0	−8.3*
		(4.7)	(4.8)	(6.0)	(6.3)
v_{oz}	m s^{-1}	0.8	1.1	1.6	1.9*
		(0.5)	(0.4)	(0.6)	(0.5)
v_{oy}	m s^{-1}	2.9	2.6	2.8	2.3
		(1.0)	(1.0)	(1.4)	(1.6)
v_{oa}	m s^{-1}	3.1	2.9	3.3	3.2
		(0.9)	(0.9)	(1.2)	(1.2)

*Indicates a significant difference ($\alpha = 0.05$) between the velocities $3\,\mathrm{m\,s^{-1}}$ and $6\,\mathrm{m\,s^{-1}}$ [one way analysis of variance with a multiple range test (Tukey-B procedure)].

Table 2. Summary of the variables of interest grouped by running velocity for shore 25 (mean and S.D.)

		$3\,\mathrm{m\,s^{-1}}$	$4\,\mathrm{m\,s^{-1}}$	$5\,\mathrm{m\,s^{-1}}$	$6\,\mathrm{m\,s^{-1}}$
N		14	14	14	14
T	10^{-3} s	282.2	241.7	206.9	181.2
		(19.0)	(20.5)	(16.8)	(11.8)
F_{zi}	kN	1.381	1.662	2.033	2.266
		(0.203)	(0.288)	(0.425)	(0.483)
t_{zi}	10^{-3} s	30.5	25.0	22.2	16.8
		(3.4)	(2.9)	(4.1)	(3.3)
G_{zi}	kN s^{-1}	86.9	115.0	166.3	232.5
		(19.7)	(27.0)	(55.4)	(81.4)
t_{Gi}	10^{-3} s	19.0	15.8	14.6	10.9
		(3.0)	(2.2)	(2.5)	(2.7)
F_{za}	kN	1.870	1.986	2.222	2.323
		(0.161)	(0.211)	(0.310)	(0.434)
α_o	degrees	99.6	98.9	100.2	101.1
		(2.8)	(2.4)	(2.2)	(3.5)
γ_o	degrees	99.3	89.1	101.0	100.9
		(3.6)	(4.4)	(4.5)	(5.5)

Table 2. (*Contd.*)

		$3\,m\,s^{-1}$	$4\,m\,s^{-1}$	$5\,m\,s^{-1}$	$6\,m\,s^{-1}$
δ_o	degrees	19.6	21.2	21.1	13.5
		(4.5)	(7.1)	(5.1)	(7.8)
ε_o	degrees	162.5	159.7	152.3	143.6
		(4.7)	(5.3)	(9.0)	(8.2)
$\Delta\gamma_{10}$	degrees	−2.5	−2.9	−6.8	−7.3
		(5.0)	(4.7)	(6.8)	(5.5)
v_{oz}	$m\,s^{-1}$	0.8	1.0	1.7	1.9
		(0.4)	(0.4)	(0.5)	(0.3)
v_{oy}	$m\,s^{-1}$	3.0	2.5	2.8	2.1
		(1.2)	(1.0)	(1.5)	(1.6)
v_{oa}	$m\,s^{-1}$	3.1	2.8	3.4	3.1
		(1.2)	(0.9)	(1.4)	(1.1)

Table 3. Summary of the variables of interest grouped by running velocity for shore 35 (mean and S.D.)

		$3\,m\,s^{-1}$	$4\,m\,s^{-1}$	$5\,m\,s^{-1}$	$6\,m\,s^{-1}$
N		14	14	14	14
T	$10^{-3}\,s$	286.5	237.0	213.0	185.0
		(22.0)	(18.6)	(16.4)	(11.5)
F_{zi}	kN	1.345	1.521	1.799	2.070
		(0.184)	(0.267)	(0.349)	(0.565)
t_{zi}	$10^{-3}\,s$	30.5	25.6	24.3	17.9
		(4.8)	(3.6)	(5.4)	(4.1)
G_{zi}	$kN\,s^{-1}$	87.6	105.0	142.8	217.0
		(20.2)	(26.8)	(49.5)	(95.7)
t_{Gi}	$10^{-3}\,s$	19.0	15.7	15.0	11.3
		(4.7)	(3.2)	(3.7)	(2.0)
F_{za}	kN	1.850	1.974	2.087	2.187
		(0.168)	(0.135)	(0.233)	(0.500)
α_o	degrees	98.5	98.8	100.5	103.0
		(2.1)	(2.1)	(2.2)	(4.4)
γ_o	degrees	100.6	102.5	103.0	103.6
		(3.6)	(4.5)	(4.7)	(5.8)
δ_o	degrees	20.2	21.2	22.4	15.5
		(4.7)	(7.2)	(6.0)	(8.1)
ε_o	degrees	162.4	160.2	154.9	141.5
		(2.7)	(5.4)	(8.2)	(8.3)
$\Delta\gamma_{10}$	degrees	−5.1	−6.3	−7.7	−9.3
		(4.8)	(5.4)	(5.8)	(7.3)
v_{oz}	$m\,s^{-1}$	0.8	1.0	1.3	1.9
		(0.5)	(0.5)	(0.7)	(0.4)
v_{oy}	$m\,s^{-1}$	2.7	2.5	3.1	2.6
		(0.8)	(0.9)	(1.5)	(1.9)
v_{oa}	$m\,s^{-1}$	2.9	2.8	3.5	3.4
		(0.7)	(0.8)	(1.3)	(1.5)

Table 4. Summary of the variables of interest grouped by running velocity for shore 45 (mean and S.D.)

		$3\,m\,s^{-1}$	$4\,m\,s^{-1}$	$5\,m\,s^{-1}$	$6\,m\,s^{-1}$
N		14	14	14	14
T	$10^{-3}\,s$	283.3	245.0	208.8	182.1
		(25.0)	(18.0)	(15.8)	(12.4)
F_{zi}	kN	1.269	1.499	1.856	2.174
		(0.265)	(0.208)	(0.383)	(0.384)
t_{zi}	$10^{-3}\,s$	24.1	23.3	19.0	15.2
		(4.6)	(2.5)	(2.7)	(3.1)
G_{zi}	$kN\,s^{-1}$	95.6	113.8	157.9	248.9
		(21.5)	(16.9)	(53.0)	(98.6)
t_{Gi}	$10^{-3}\,s$	14.4	13.2	11.1	8.5
		(3.4)	(2.2)	(2.6)	(2.0)
F_{za}	kN	1.860	1.949	2.104	2.278
		(0.183)	(0.181)	(0.287)	(0.296)
α_o	degrees	98.6	99.2	99.8	101.4
		(1.9)	(2.2)	(2.3)	(2.9)
γ_o	degrees	98.9	99.5	100.0	100.6
		(4.3)	(4.4)	(5.8)	(3.5)
δ_o	degrees	21.2	21.4	20.0	14.2
		(4.7)	(6.7)	(5.1)	(7.6)
ε_o	degrees	161.8	159.2	152.3	143.0
		(4.0)	(6.5)	(7.4)	(8.7)
$\Delta\gamma_{10}$	degrees	−5.9	−5.5	−6.3	−8.3
		(3.5)	(3.1)	(5.2)	(5.7)
v_{oz}	$m\,s^{-1}$	0.9	1.1	1.7	2.1
		(0.5)	(0.5)	(0.6)	(0.5)
v_{oy}	$m\,s^{-1}$	3.0	2.9	2.5	2.2
		(0.7)	(1.0)	(1.0)	(1.4)
v_{oa}	$m\,s^{-1}$	3.1	3.2	3.1	3.2
		(0.7)	(0.8)	(0.8)	(1.0)