GROUND REACTION FORCES AND SPATIO-TEMPORAL VARIABLES DURING BAREFOOT AND SHOD RUNNING

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INTRODUCTION

During the last decade, a lot of investigators studied the influence of the mechanical characteristics of the shoe on the ground reaction forces during foot contact and stance phase in running in order to have a better understanding of the "in-vivo" cushioning properties of the shoe and to find which shoe parameters could reduce high impact forces. Unequivocal results have been represented because the running technique varies depending on the shoe and surface hardness (Lees, 1988). On the other hand, a study of Robbins and Hanna (1987) mentioned a very low frequency of running-related injuries in barefoot populations. But few studies investigated barefoot running and most of these studies were based on limited statistical samples.

The purpose of this study was to investigate the variations in step length, step frequency and ground reaction forces between barefoot and shod-foot running at three different velocities.

METHODS

Nine trained male runners were tested (age : 27.3 ± 9 years , height : 1.78 ± 0.07 m , weight : 70 ± 9 kg, shoe size : US 8.9 ± 1.5) All of them were free of injuries at the time of the experiment. The persons were running barefoot and shod (Adidas 033153, T-response) at three different velocities : 3.5, 4.5 and 5.5 $m.s^{-1}$ ± 0.2 $m.s^{-}$.

To measure the ground reaction forces, a Kistler force plate (frequency of resonance > 800 s^{-1}, 12bit A-D conversion at 1666 s^{-1}) was mounted in the center of a 40-m indoor runway. Running velocity was computed from the time interval measured by photocells mounted 4m from the center of the force platform in both directions at shoulder height. The runners contacted the force platform with the right foot, without altering their technique. Every person performed the test until ten good trials were made for each condition (shoe and velocity).

The first vertical impact force peak was characterized by measuring the maximal amplitude (F_{zi}) and the time of its occurrence (t_i). The average impact loading rate was computed by dividing the maximal amplitude by its time of occurrence ($G_{zi} = F_{zi}/t_i$). Since more than one impact peak was seen in barefoot running, the largest one was analyzed. (For 8 persons this was also the first one). The amplitude and time of the minimal and active force peak (resp. F_{zmin} and t_{min}, F_{za} and t_a) and total foot contact time (t_{cont}) were also measured.

Two Nac high-speed camera's (Nac 400 at 200 $frames.s^{-1}$ and Nac 1000 at 500 $frames.s^{-1}$) filmed the test persons in the sagittal plane while a Nac-400 camera at 200 $frames.s^{-1}$ filmed the runners from behind. Step length and step frequency were measured by film analysis.

First, a mean value of the ten trials for each variable was computed. Then, the average value of the nine persons was taken. Statistical differences between different conditions were tested with a two-factor Anova test with repeated measures (shoe x velocity), with a significance level $p \leq .05$.

RESULTS AND DISCUSSION

	3.5 m.s^{-1}				4.5 m.s^{-1}				5.5 m.s^{-1}			
	barefoot		shod		barefoot		shod		barefoot		shod	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
step frequency (s^{-1}) *◊	2.74	0.17	2.64	0.18	2.87	0.20	2.73	0.21	3.03	0.19	2.85	0.14
step length (m) *◊	1.280	0.083	1.330	0.089	1.582	0.132	1.600	0.119	1.855	0.136	1.918	0.107
t_{cont} (s) *◊	0.239	0.008	0.251	0.011	0.200	0.008	0.219	0.014	0.175	0.011	0.193	0.012

Table 1. Spatio-Temporal Variables (Means and Standard Deviations of nine persons; * = significant main effect of velocity; ◊ = significant main effect of condition)

The results for the spatio-temporal variables are presented in Table 1. All variables change significantly with increasing speed. Increasing the velocity from 3.5 to 5.5 m.s^{-1} shows a larger step frequency, a smaller step length and a shorter foot contact time.
A significant larger step frequency, and a smaller step length (not significant for 4.5 m.s^{-1}) and contact time were found for the barefoot condition.
These results support the findings in previous studies (Komi et al, 1987; Cavanagh et Cram, 1990). It shows that simple kinematic parameters are sensitive to environmental changes. A possible explanation for the smaller step length in barefoot running could be that the runners adapt a strategy to decrease the local stress underneath the heel (= pain sensation). Taking smaller steps results in a larger plantar flexion of the bare foot at touchdown.

	3.5 m.s^{-1}				4.5 m.s^{-1}				5.5 m.s^{-1}			
	barefoot		shod		barefoot		shod		barefoot		shod	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
F_{zi} (N) *	1243	207	1275	176	1642	324	1574	257	1928	668	1898	376
F_{zi} (%BW) *	183	31	189	32	242	47	232	41	286	100	279	56
t_i (ms) *◊	14	5	38	6	11	5	33	5	8	3	30	4
G_{zi} (N.ms^{-1}) *◊	101	24	34	9	162	47	49	12	267	152	66	21
F_{zmin} (N) *◊	858	211	1142	127	1042	266	1314	184	1108	247	1494	262
F_{zmin} (%BW) *◊	125	22	168	21	151	25	193	26	163	33	219	32
t_{min} (ms) *◊	30	5	48	4	26	6	45	4	23	5	43	4
F_{za} (N) *	1814	273	1892	243	1973	297	2021	289	2086	336	2112	295
F_{za} (%BW) *◊	265	17	277	15	288	20	296	20	305	25	309	23
t_a (ms) *◊	94	8	104	7	81	9	92	8	71	8	82	5

Table 2. Variables of the Vertical Ground Reaction Forces (Means and Standard Deviations of nine persons; %BW = percentage of Body Weight ; * = significant main effect of velocity; ◊ = significant main effect of condition)

Table 2 shows the results of the vertical ground reaction forces. For all variables there is a significant main effect of running speed. The vertical impact force amplitude (F_{zi}) increased about 50% (barefoot and shod) when velocity increases from 3.5 to 5.5 $m.s^{-1}$. The loading rate (G_{zi}) even increased for more than 100% in the barefoot condition. These results are expected based on previous studies (Hamill et al, 1983; Nigg et al, 1987).
Figure 1 demonstrates for one person the representative curves of the vertical reaction force at 4.5 $m.s^{-1}$. A significant main effect of condition (barefoot-shod) was found for all variables except for the amplitude of the impact (F_{zi}) and active (F_{za}) force. But the time to reach the impact force peak (t_i) is significantly smaller in barefoot running which causes the maximal loading rate (G_{zi}), an important variable determining the impact load during heelstrike, to be significantly larger in the barefoot condition (see figure 2). These results are supported by previous studies (De Clercq et al, 1994; De Koning et al, 1993, Dickinson et al, 1985).Cole et al (1995) used a 3-dimensional model to determine the contact forces in the joints of the foot and ankle during barefoot and shod running. They found a significant larger magnitude and rate of musculo-skeletal loading in barefoot running. Although there is no experimental prove, it is empirical assumed that a high loading rate causes tissue degeneration and cartilage changes.
During push-off no important differences were found.

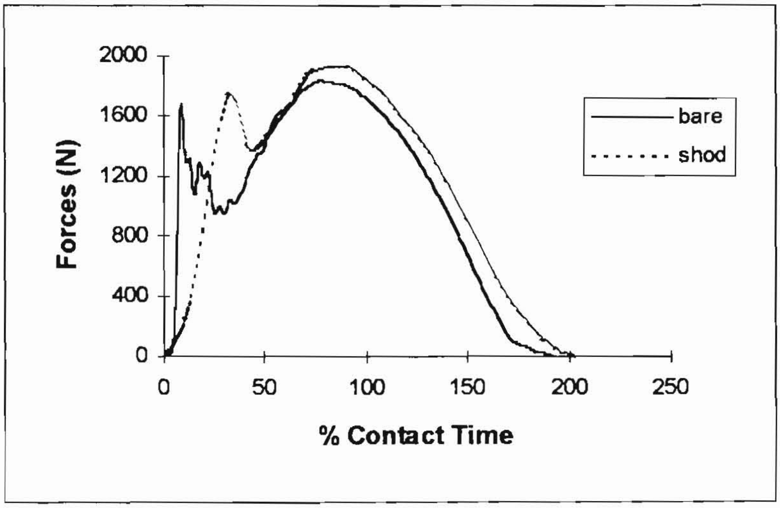

Figure 1. The vertical force-time curve of a barefoot and shod trial of one person at 4.5 $m.s^{-1}$.

These results support the thesis that the running shoe and heel pad act together as a superior cushioning system. In barefoot running a fast maximal deformation of the fatty heel tissue reduces its shock reduction capacity at heelstrike (De Clercq et al, 1994).
The results of this study indicate that there is an adaptation to the shoe during running. Analysis of the kinematic parameters of these nine persons will explain more clearly the results found till now.

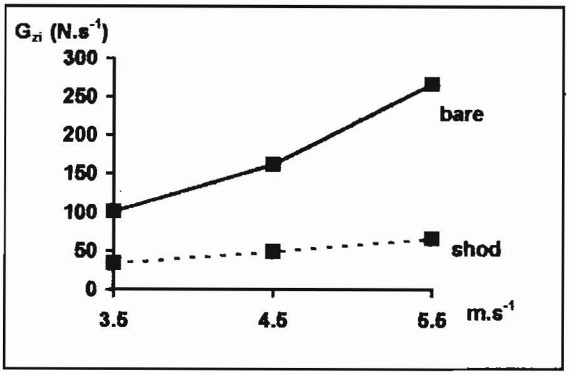

Figure 2. Influence of running speed and condition on the vertical force loading rate

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