ELSEVIER

Journal of Biomechanics 33 (2000) 269–278

JOURNAL
OF
BIOMECHANICS

www.elsevier.com/locate/jbiomech

Biomechanical analysis of the stance phase during barefoot and shod running

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Received 6 February 1998; accepted 13 October 1999

Abstract

This study investigated spatio-temporal variables, ground reaction forces and sagittal and frontal plane kinematics during the stance phase of nine trained subjects running barefoot and shod at three different velocities (3.5, 4.5, 5.5 m s^{-1}). Differences between conditions were detected with the general linear method (factorial model). Barefoot running is characterized by a significantly larger external loading rate than the shod condition. The flatter foot placement at touchdown is prepared in free flight, implying an actively induced adaptation strategy. In the barefoot condition, plantar pressure measurements reveal a flatter foot placement to correlate with lower peak heel pressures. Therefore, it is assumed that runners adopt this different touchdown geometry in barefoot running in an attempt to limit the local pressure underneath the heel. A significantly higher leg stiffness during the stance phase was found for the barefoot condition. The sagittal kinematic adaptations between conditions were found in the same way for all subjects and at the three running velocities. However, large individual variations were observed between the runners for the rearfoot kinematics. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Barefoot running; Ground reaction forces; Sagittal plane kinematics; Frontal plane kinematics; Kinematic adaptation

1. Introduction

Nowadays running can be considered one of the most important recreational activities. Since most people are running shod, many scientific studies investigated the influence of alterations in the properties of the shoe on the running style. Ground reaction forces and kinematic variables were found to vary with shoe hardness and shoe geometry (Nigg, 1986; Nigg and Morlock, 1987; Lees, 1988; Pratt, 1989; Edington et al., 1990; Van Woensel and Cavanagh, 1992; McNair and Marshall, 1994). The relationship between kinematic and external and internal kinetic variables was also studied using dynamic simulation models (Denoth, 1986; Gerritsen et al., 1995; Wright et al., 1998).

But there are still many aspects concerning the manner in which athletes adapt to different surfaces, shoes and other boundary conditions which are not well understood. This insight could be enhanced by studying the difference in kinematics between barefoot and shod running since in these situations boundary conditions influencing running kinematics are manipulated. Barefoot running can be seen as a running condition wherein external protection and shock reduction is minimal. So, alterations in running style are expected to be more pronounced than when comparing different shod conditions.

Until now, several authors studied barefoot running but conflicting results were presented in literature, probably because of limited samples. However, all studies agreed with the fact that the external loading rate is significantly larger in the barefoot condition (Dickinson et al., 1985; Komi et al., 1987; Lees, 1988; De Clercq et al., 1994). Concerning the sagittal plane kinematics a more extended body position and a smaller touchdown velocity of the foot were found during barefoot running (De Koning and Nigg, 1993).

The aim of the current study is to provide a comprehensive description of barefoot running using a statistical representative data set, and to compare barefoot with shod running. Therefore, spatio-temporal variables, ground reaction forces and sagittal and frontal plane

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0021-9290/00/$ - see front matter
PII: S0021-9290(99)00192-X

kinematics of barefoot and shod running at three different velocities are analyzed and compared. In that way, systematic adaptations in the running style can be detected and hypotheses about the underlying mechanisms will be formulated.

2. Method

2.1. Subjects and experimental protocol

Nine trained male long distance runners (30–40 km week^{-1}) were tested while running barefoot and shod (neutral jogging shoe; Adidas 033153, T-response) at three different velocities (3.5, 4.5 and 5.5 m s^{-1}). All of them were free of injuries at the time of the experiment. They were informed about the procedures and signed an informed consent. The average characteristics were: age: 27.3 ± 9 yr; height: 1.78 ± 0.07 m; body mass: 70 ± 9 kg; shoe size: UK 8.9 ± 1.5.

The three orthogonal components of the ground reaction forces were measured with a Kistler force plate (frequency of resonance > 800 s^{-1}, 12bit A-D conversion at 1666 s^{-1}) mounted in the center of a 30 m indoor tartan runway and connected with a PC (Ariel Performance Analysis System Inc) to obtain online a graphical representation of the analogue signals (Fig. 1). Running velocity was computed from the time interval measured by infrared photocells mounted at shoulder height in both directions 2.25 m from the center of the force platform (a deviation of 5% of the intended velocity was permitted).

Foot movements were video-taped in the sagittal and frontal plane. Sagittal plane images of the right leg were obtained from two high-speed video-cameras. One (Nac 500; 250 Hz) provided images of the whole body, while another (Nac 1000; 500 Hz) showed a detailed view of the shank and foot during the stance phase. A dorsal camera (Nac 400) obtained frontal images at 200 Hz. Five LED lights were placed in the visual plane of all video-cameras. These LED lights were electronically activated with a time difference of 0.001 s each. Using these light signals, the video-cameras and the force plate were synchronized with a precision of 0.001 s.

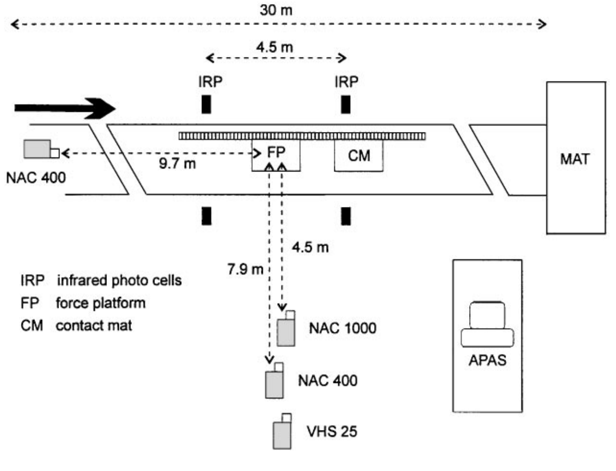

Fig. 1. Experimental setup.

Each runner was given enough time to warm up and become familiar with the specific condition and velocity. The runners contacted the force plate with the right foot without altering their technique. This was checked visually where the most important criterion was an equal braking/propulsive impulse exerted during foot contact (Nigg, 1986). Subjects performed the test until 10 good trials for each condition and velocity were made.

For seven runners, additional tests were performed while running barefoot at 4.5 m s^{-1}. A pressure mat was placed on top of the Kistler force plate in order to measure dynamic local pressures (Footscan® system, sampling frequency of 200 Hz, 4 sensors cm^{-2}). The local pressure underneath the heel was obtained by averaging the pressures measured by the sensors located underneath the tuber calcaneum.

2.2. Collection of data

Step length was calculated with an accuracy of 0.01 m. The inverse of the step time between heel contact of right and left foot as seen on the frontal plane video-images (accuracy 0.005 s) gave the step frequency.

The three orthogonal components of the ground reaction forces were measured. The variables of the vertical forces that were analyzed are described in Table 1.

Markers in the sagittal plane were placed on the skin according to Bobbert et al. (1992) (Fig. 2a). The marker on the hip was placed 0.02 m proximal to the greater trochanter, at the knee joint in the center 0.02 m above the tibial plateau and at the ankle joint at the lateral malleolus, 0.005 m anterior to its tip. The shoulder marker was put at the height of the acromion.

In the barefoot condition, foot markers were placed at the tuber calcaneum and at the fifth metatarsal joint. In the shod condition, those markers were placed on the shoe at the height of those landmarks. Relative and absolute joint- and segment-angles were measured as indicated in Fig. 2a.

Statistics were applied on numeric values collected at distinct points: at 30 ms before touchdown; at touchdown ($t = t_0$); at the time of the first vertical impact force ($t = t_\mathrm{i}$); at the end of midstance (i.e. the moment the heel leaves the ground) and at push-off (i.e. the moment the forefoot leaves the ground; $t = t_\mathrm{cont}$).

To analyze the foot and ankle movements in the frontal plane, markers were placed according to Clarke et al. (1983); Fig. 2b): (a) in the middle of the heel; (b) on

Table 1
Description of the calculated variables of the ground reaction forces, frontal plane kinematics and pressure measurements

Variable	Description	Unit
F_{zi}	amplitude of the first vertical impact force	N; body weight (BW)
t_i	time of occurrence of F_{zi}	s
G_{zi}	maximal vertical loading rate between touchdown and t_i	BW s^{-1}
F_{zmin}	amplitude of the minimal vertical force	BW
t_{min}	time of occurrence of F_{zmin}	s
F_{za}	amplitude of the vertical active force peak	BW
t_a	time of occurrence of F_{za}	s
t_{cont}	total contact time of the stance phase	s
$\Delta\gamma_{imp}$	change of the calcaneal eversion from touchdown to the occurrence of the impact peak	deg
local pressure	the maximal pressure measured by sensors located underneath the tuber calcaneum	N cm^{-2}

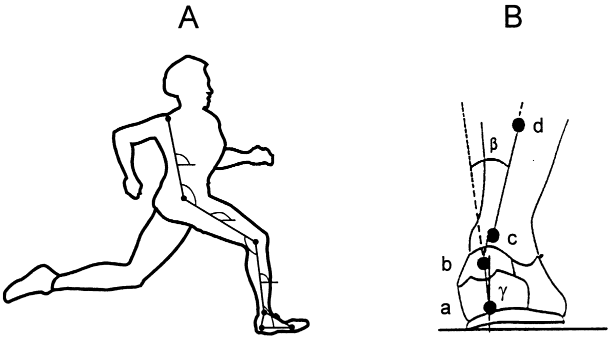

Fig. 2. Placement of the markers in the sagittal (A) and frontal plane (B;) with the calculated angles.

the upper part of the calcaneus; (c) on the Achilles tendon at the height of the malleoli; (d) 15 cm above c in the middle of the leg.

The temporal evolution of rearfoot angle (γ) and Achilles tendon angle (β) were determined. The rearfoot angle (in deg) was measured from AB to the vertical plane, where a negative value points at calcaneal eversion. The Achilles tendon angle was measured from AB to CD, where a negative value points at eversion. According to the Cavanagh/Clarke convention (Edington et al., 1990), the latter relative angle is used to describe subtalar inversion and eversion.

Video-images were digitized using the Ariel Performance Analysis System for two-dimensional calculation. The frontal plane kinematics were filtered with a low-pass digital filter with a cutoff frequency of 18 Hz, a procedure recommended in literature about rearfoot kinematics (Hamill et al., 1994). For sagittal plane kinematics, no digital filtering was used. Previous studies showed incorrect values of the second derivative at the endpoints of the data set when using a digital filter or cubic spline, whereas better results were obtained with the quintic spline routines (Woltring, 1985; Wood, 1982). A quintic spline routine was used in the current study to smooth the x- and y-coordinates of the sagittal plane variables. The standard error of the smoothing procedure was individually determined and varied between 0.12 and 0.2 cm. The frame before, during and after touchdown of the heel was not smoothed. In this way, the sudden decrease of heel velocity caused by collision of the foot with the ground was not attenuated.

A possible limitation of the current study is the use of a two-dimensional technique. Areblad et al. (1990) reported that most two-dimensional angular values measured from a posterior view were very sensitive to the alignment angle between the foot and the camera axis. However, small errors were observed for relative pronation angles during midstance. A comparative statistical analysis of Van Gheluwe et al. (1995) between a two- and a three-dimensional approach of calculating rearfoot kinematics showed comparable results for the variables between touchdown and midstance. Additionally, a two-dimensional method is a standard technique in literature for evaluating rearfoot kinematics. If properly applied, reliable data can be obtained (Edington et al., 1990; Hamill et al., 1994). Nevertheless, the lack of information about longitudinal rotation of the leg segments is a limitation of the two by two-dimensional method.

2.3. Statistical design

The ground reaction forces were calculated for all 10 trials, from which 5 trials for each condition and velocity were analyzed for the kinematic results. This yields to a dataset of 540 trials for the ground reaction forces and 270 for the kinematic results. Mean and standard deviation were used to describe the individual and general results. Statistical effects of velocity and condition were tested with the statistical package SPSS (SPSS inc.) using GLM (general linear method), factorial model, with a significance level $p \leq 0.05$. Both interactions between factors and the effects of individual factors were investigated. All trials were included and treated as repeated measurements. The Pearson product moment correlation was used to provide single correlations, while a linear regression (stepwise method) gave the coefficients of a linear equation, involving several independent variables that best predict the value of one dependent variable.

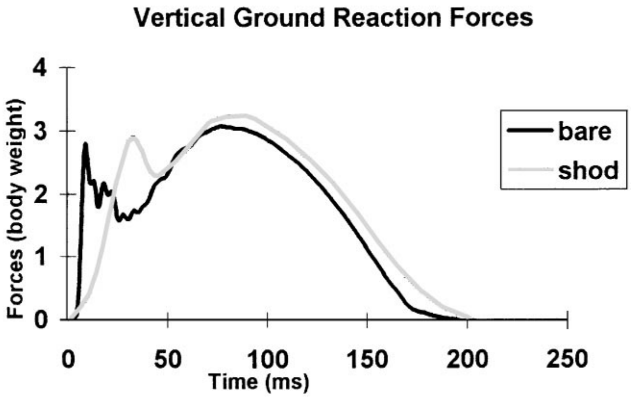

Fig. 3. Vertical ground reaction curves of 1 representative person (1 trial barefoot and 1 trial shod) at a velocity of 4.5 m s^{-1}.

3. Results

3.1. Spatio-temporal variables

The results are presented in Table 2. For all the tested velocities, runners take significantly smaller steps at a higher frequency for the barefoot condition and a shorter contact time was found.

3.2. Kinetic variables

Fig. 3 shows the representative curves of one runner for the vertical ground reaction forces at 4.5 m s^{-1}. Barefoot running is characterized by a significantly larger loading rate than in shod running and, in general, more than one impact peak was found for the barefoot condition. No significant main effect of condition (barefoot-shod) was observed for the amplitude of both the impact force peak (F_{zi}) and the active force peak (F_{za}). The results are presented in Table 2. The maximal local pressure underneath the heel was for the barefoot condition 97 ± 35 N cm^{-2} (while running at 4.5 m s^{-1}).

3.3. Sagittal and frontal plane kinematics

Mean sagittal plane joint and segment angles for all velocities are presented in Table 3. Fig. 4 shows the mean stick figure for all subjects at 4.5 m s^{-1} at four discrete time intervals: (A) touchdown; (B) at the time of the vertical impact force peak; (C) at the end of midstance (the moment the heel leaves the ground); (D) at toe-off.

Both the occurrence of the impact peak and the end of midstance are reached significantly faster for barefoot running than for shod running (Tables 2 and 3). Most statistical differences are found at the level of the distal segments during the initial contact of the foot.

Concerning the frontal plane kinematics, a significantly smaller initial eversion at impact ($\Delta\gamma_{imp}$) was observed for the barefoot condition. All the other variables describing rearfoot kinematics (γ) and subtalar eversion/inversion (β) displayed significant interaction effects of subjects with condition.

4. Discussion

In the current study differences in kinematics and in ground reaction forces, between running with and without running shoes, were studied in order to gain more insight in the adaptation of athletes to changes in the mechanical characteristics of the foot–ground interface.

Table 2

Spatio-temporal and kinetic variables (means and standard deviations of nine persons, 10 trials; BW = body weight; v = significant main effect of velocity ($p < 0.05$); c = significant main effect of condition ($p < 0.05$))

$N = 9$		3.5 m s^{-1}				4.5 m s^{-1}				5.5 m s^{-1}					
10 trials		Bare		Shod		Bare		Shod		Bare		Shod			
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD		
Step freq	(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	v	c
Step length	(m)	1.28	0.08	1.33	0.09	1.57	0.13	1.61	0.12	1.85	0.14	1.92	0.11	v	c
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	v	c
t_{flight}	(s)	0.127	0.023	0.129	0.026	0.151	0.023	0.151	0.025	0.156	0.020	0.156	0.019	v	
F_{zi}	(BW)	1.8	0.3	1.9	0.3	2.4	0.5	2.3	0.4	2.8	0.1	2.8	0.6	v	
t_i	(s)	0.014	0.005	0.038	0.006	0.011	0.005	0.033	0.005	0.008	0.003	0.030	0.004	v	c
G_{zi}	(BW s^{-1})	409	139	91	35	575	203	123	48	731	307	186	87	v	c
F_{zmin}	(BW)	1.2	0.2	1.7	0.2	1.5	0.2	1.9	0.3	1.6	0.4	2.1	0.3	v	c
t_{min}	(s)	0.030	0.005	0.048	0.004	0.026	0.006	0.045	0.004	0.023	0.005	0.043	0.004	v	c
F_{za}	(BW)	2.6	0.2	2.8	0.1	2.9	0.2	2.9	0.2	3.0	0.2	3.1	0.2	v	
t_a	(s)	0.094	0.008	0.104	0.007	0.081	0.009	0.092	0.008	0.071	0.008	0.082	0.005	v	c

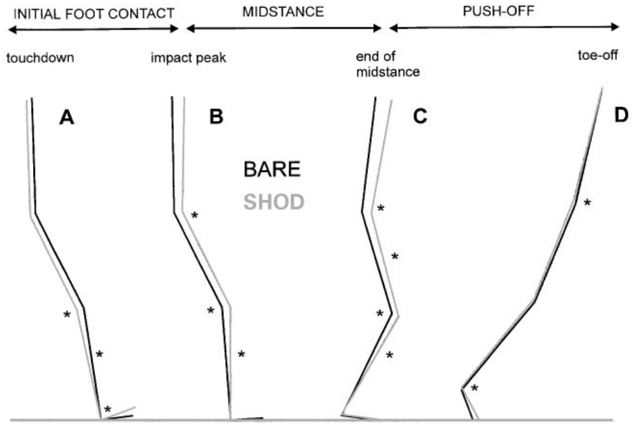

Fig. 4. Mean stick figure at a velocity of 4.5 m s^{-1}. * = significant main effect of condition ($p < 0.05$). The barefoot condition is shown as the black line and the shod condition as the grey line.

In barefoot running, a significantly larger loading rate during impact (G_{zi}) was found, agreeing with results of previous studies (Dickinson et al., 1985; De Koning and Nigg, 1993; De Clercq et al., 1994). Two studies demonstrated this G_{zi} to be a prime correlating variable with the subjects perception of impact severity (running: Hennig et al., 1996; simulated impact with human pendulum: Lake and Lafortune, 1998). Therefore, based on this literature, one could assume that the runners will adapt their running style in an "impact-reducing" way when running barefoot. However, results of the current study do not confirm this, as will be discussed in the impact section.

The characteristics of the vertical ground reaction force during the impact phase (at the most the first 0.05 s of stance) depend upon the initial conditions at touchdown and, subsequently, upon the way the segments of the body are decelerated during the impact phase (Bobbert et al., 1992). The results will be discussed in this order. After this impact-related discussion, attention will be paid to more general kinematic changes during the entire foot contact phase.

4.1. Impact

Regarding the sagittal plane kinematics at touchdown, most statistical differences are found at the level of the distal segments (see Fig. 4A). In barefoot running, placement of the foot is significantly more horizontal than in the shod condition: the absolute difference for the sole angle between the two conditions is 14° at 4.5 m s^{-1} (12° at 3.5 m s^{-1};15° at 5.5 m s^{-1}). This flatter foot placement results from a significantly larger plantar flexion of the ankle and a significantly more vertical position of the shank in the barefoot condition. The latter is caused by a larger knee flexion because there is no difference in thigh orientation at touchdown between barefoot and shod running. This larger knee flexion was also found by De Koning and Nigg (1993).

Some studies adopted a modelling approach to investigate the relationship between the initial kinematic conditions at touchdown and the vertical impact force peak. These dynamic simulations showed that impact loading can be reduced by decreasing the vertical momentum of the caudal body parts (Gerritsen et al., 1995) and by adopting a touchdown geometry that favours deceleration (Denoth, 1986; Gerritsen et al., 1995). Surprisingly, in barefoot running, the subjects of the present study ran with a non-different vertical touchdown velocity and with a flatter foot placement (more plantar flexion), which does not concur at all with a strategy to reduce the severity of impact.

It is interesting to note that this more horizontal foot placement is prepared well before touchdown. In the barefoot condition, the ankle is already significantly more plantar flexed at 0.03 s before touchdown and the knee becomes significantly more flexed from 0.02 s before touchdown. A linear regression was calculated between the sole angle at touchdown as dependent variable and shank segment angle and ankle angle, both at 0.03 s before touchdown, as independent variables (see Table 4: $r = 0.92$ barefoot; $r = 0.93$ shod; both $p < 0.05$). So, the joint configuration of the leg at touchdown is prepared in free flight, implicating an actively induced adaptation strategy to barefoot running.

The flatter foot placement in barefoot running could be explained by another functional demand. In previous research it was shown that at first ground contact the heel pad is suddenly deformed to a physiological maximum when running barefooted (De Clercq et al., 1994). The deformation of the fatty heel tissue is proportional to the local stress acting on the plantar side of the bare heel. This means that for a given vertical impact force — the F_{zi} being non-different in barefoot/shod—, the local pressure on the heel can be reduced by adopting a flatter foot placement, through which initial ground contact covers a larger plantar area. In this way overloading of the heel could be prevented. Indeed, in the barefoot running condition the maximal local pressure underneath the heel correlates negatively with the sole angle at touchdown ($r = -0.7$, $p < 0.05$). The more horizontal the foot, the smaller the maximal pressure acting on the heel.

It is also remarkable that the horizontal component of the touchdown velocity is significantly smaller in barefoot running. This could give rise to a reduction in shear forces acting on the heel, but in the current experiment we could not obtain reliable fore-after ground reaction forces during the impact phase. Nevertheless, as sensation of mechanical inputs and pain is well established in the foot sole (Bojsen-Moller and Jorgensen, 1991) it is assumed that runners adopt a flatter foot placement in barefoot running in an attempt to limit the local pressure

Table 3
Frontal and sagittal plane kinematics (means and standard deviations of nine persons, 5 trials; v = significant main effect of velocity ($p < 0.05$); c = significant main effect of condition ($p < 0.05$))

$N = 9$		$3.5\ \mathrm{m\,s^{-1}}$				$4.5\ \mathrm{m\,s^{-1}}$				$5.5\ \mathrm{m\,s^{-1}}$					
5 trials		Bare		Shod		Bare		Shod		Bare		Shod			
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD		
$\Delta\gamma_{\mathrm{imp}}$ (deg)		1.7	1.9	5.2	2.5	1.7	2.4	5.0	2.0	1.2	1.5	5.2	2.8		c
End of midstance (s)		0.102	0.005	0.123	0.005	0.088	0.004	0.113	0.010	0.073	0.009	0.096	0.012	v	c
Displ hip (stance) (cm)		79.1	4.1	84.2	4.5	85.5	4.7	91.9	5.5	91.6	6.3	98.1	6.7	v	c
Displ hip (flight) (cm)		48.9	9.4	48.8	10.5	72.4	12.1	68.0	12.2	93.4	11.0	93.9	14.0	v	
Hor displ hip-heel		19.9	3.5	22.9	3.7	23.4	3.0	27.3	3.4	25.5	2.8	29.9	4.6	v	c
(cm)	touchdown														
Vert. decel. distance ankle		1.1	0.4	1.9	0.3	1.1	0.3	2.1	0.4	1.2	0.4	2.2	0.4		c
(cm)															
Kleg		36.7	9.2	30.1	7.6	42.2	21.0	31.4	6.3	42.2	10.6	36.8	13.4		c
$\mathrm{KN\,m^{-1}}$															
Ankle angle	−30 ms	90.0	4.7	81.9	5.5	91.3	5.9	81.6	5.2	92.0	7.5	82.2	5.8		c
(deg)	touchdown	90.4	4.6	82.2	5.0	91.8	5.7	81.7	4.5	93.5	6.6	82.8	5.9	v	c
	impact	91.0	3.4	90.0	3.6	92.2	3.2	91.5	3.2	94.3	3.9	91.9	4.0	v	
Sole angle	−30 ms	12.9	5.6	21.9	4.9	15.2	7.2	26.6	4.9	16.8	7.6	28.3	6.3	v	c
(deg)	touchdown	6.4	4.5	18.0	5.0	6.6	5.6	20.8	4.9	5.5	6.1	20.3	6.9		c
	impact	2.0	3.3	−1.4	1.7	2.1	3.8	−0.6	2.2	1.5	4.0	−0.8	2.6		
Shank	−30 ms	102.9	3.4	103.3	2.9	106.6	3.0	107.6	2.8	108.9	3.4	109.9	3.1	v	c
segm angle	touchdown	96.8	2.1	99.8	1.6	98.6	1.5	102.1	1.4	98.9	1.6	102.7	2.1	v	c
(deg)	impact	92.9	3.6	87.9	2.4	94.4	3.3	90.3	2.7	95.4	1.7	90.4	2.8	v	c
	end midst	64.2	2.1	61.7	2.9	64.1	2.0	60.5	2.8	64.2	3.1	61.0	4.0		c
Thigh	touchdown	113.3	2.5	112.2	2.1	116.4	2.3	115.6	1.8	119.3	1.5	119.3	2.2	v	
segm angle	impact	113.7	2.4	114.1	3.0	116.6	2.3	116.3	2.7	119.0	1.6	118.4	3.1	v	
(deg)	end midst	105.3	2.6	104.3	3.1	106.2	2.6	104.4	2.9	107.9	2.6	106.2	3.3	v	c
Knee angle	−20 ms	168.8	4.5	171.1	3.6	168.5	3.3	170.7	3.4	168.5	3.8	168.1	3.5	v	c
(deg)	touchdown	163.5	3.5	167.6	2.1	162.2	2.3	166.5	2.0	159.5	2.0	163.4	1.9	v	c
	impact	159.1	4.5	153.8	4.6	157.8	3.4	154.0	4.8	156.4	2.0	151.9	4.4	v	c
	end midst	139.0	4.3	137.4	4.1	137.9	4.3	136.2	4.3	136.3	3.7	134.8	4.2	v	c
Knee angle	−20 ms	−172.3	142.8	−81.1	144.7	−225.8	133.1	−127.0	161.7	−263.2	149.8	−139.6	141.7		c
velocity	touchdown	−306.1	121.2	−251.6	113.0	−353.4	136.5	−265.3	128.3	−359.1	139.4	−288.8	136.6		c
$(\mathrm{deg\,s^{-1}})$	impact	−371.1	103.4	−447.7	86.6	−413.1	125.2	−474.0	111.1	−413.9	121.1	−472.2	139.9		c
Max knee flexion		137.6	4	135.8	5	136.9	4	134.9	4.6	135.6	3.9	133.7	4.6		c
(deg)															
Time of max knee flexion (%)		36.3	3	41.3	2	38.1	2.6	44.4	2.2	40.1	3.6	44.6	2.7	v	c
contact time															
Heel vel	touchdown	1.23	0.28	1.67	0.26	1.39	0.27	1.86	0.29	1.54	0.33	1.99	0.32	v	c
$(\mathrm{m\,s^{-1}})$	impact	0.57	0.22	0.24	0.08	0.64	0.29	0.37	0.11	0.85	0.22	0.45	0.10	v	c
Hor heel vel	touchdown	1.11	0.26	1.58	0.29	1.16	0.29	1.64	0.35	1.21	0.38	1.67	0.38		v
$(\mathrm{m\,s^{-1}})$	impact	0.52	0.20	0.22	0.07	0.58	0.25	0.31	0.10	0.75	0.21	0.37	0.09	v	c
Vert heel vel	touchdown	−0.51	0.13	−0.52	0.13	−0.74	0.12	−0.84	0.12	−0.90	0.16	−1.04	0.13	v	
$(\mathrm{m\,s^{-1}})$	impact	−0.19	0.15	0.08	0.07	−0.21	0.21	0.17	0.10	−0.32	0.19	0.20	0.14		c

Table 4
Regression equations between the sole angle at touchdown and the ankle and shank angle at 30 ms before touchdown (a and b) and at touchdown (c and d)

Equations for both conditions are:			
(a) Barefoot:	sole-angle(0) = 34.5 − 1.0 ankle angle(− 0.030 s) + 0.6 shank angle(− 0.030 s)		
	r: 0.92	r^2: 0.85	$p < 0.05$
(b) shod:	sole-angle(0) = 39.1 − 0.9 ankle angle(− 0.030 s) + 0.5 shank angle(− 0.030 s)		
	r: 0.93	r^2: 0.87	$p < 0.05$
(c) Barefoot:	sole-angle(0) = − 4.8 − 1.0 ankle angle(0) + 1.0 shank angle(0)		
	r: 0.98	r^2: 0.96	$p < 0.05$
(d) Shod:	sole-angle(0) = 7.4 − 1.0 ankle angle(0) + 0.9 shank angle(0)		
	r: 0.98	r^2: 0.97	$p < 0.05$

underneath the heel. This assumption accords with the findings of Hennig et al. (1996), who measured a substantial reduction in heel loading, with a shift towards more weight bearing in the forefoot, when running with shoes with harder soles.

Concerning the initial ground contact phase (from touchdown till the time of the vertical impact peak force) the vertical deceleration distance of the ankle is significantly reduced in barefoot running (difference between barefoot and shod at 3.5 m s^{-1}: 0.8 cm; at 4.5 m s^{-1}: 1.0 cm; at 5.5 m s^{-1}: 1.0 cm; $p < 0.05$). This can be attributed to the absence of a deformable shoe sole and to a smaller movement range for plantar flexion through the flatter foot placement in barefoot running. When observing the frontal plane kinematics, the initial eversion between contact and the occurrence of the impact peak ($\Delta\gamma_{\text{imp}}$) is also significantly smaller for barefoot than for shod running. According to the biomechanical model of Stacoff et al. (1988), a larger initial eversion offers an additional deceleration mechanism during initial foot contact. As a consequence, following the extensive mechanical analysis of the landing phase in running by Bobbert and co-workers (1992), the momentum of the support leg will be less adequately decelerated in barefoot running. In the current study, a compensation is found in the higher knee flexion velocity during the first 30 ms in barefoot running (see Fig. 5), matching with a strategy to reduce impact loading by reducing the effective mass of the contacting leg (Wright et al., 1998). However, these authors showed with a forward dynamic simulation model that this higher knee flexion velocity occurred immediately after touchdown as a passive result from running with shoes with harder soles. In the current study, it should be stressed that in barefoot running this faster knee flexion originated 0.02 s before touchdown (see Table 3; Fig. 5), again pointing at an actively induced adaptation in running style when comparing barefoot to shod running. The actively induced kinematic adaptations in the current study are also in line with the EMG data of Komi et al. (1987) which showed a higher preactivation level of the gastrocnemius muscle for the barefoot condition than for the shod condition.

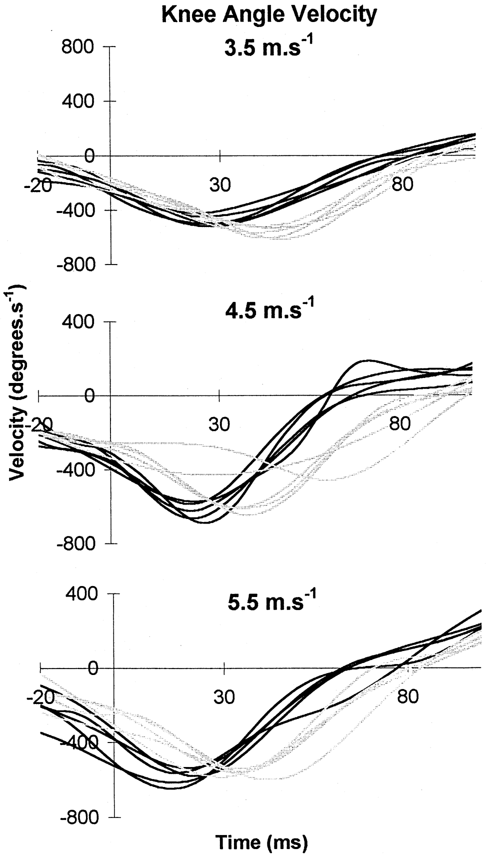

Fig. 5. Knee angle velocity curves of a representative subject at the three running velocities. The barefoot condition is shown as the black line and the shod condition as the grey line. The figure shows a time interval between 20 ms before touchdown and 100 ms after touchdown.

All the above discussed sagittal plane kinematic adaptations to barefoot running were in the same way for all subjects and for the three running speeds tested in the current study indicating a pronounced adaptive strategy.

Considering barefoot running as an extreme hard shoe-condition, results of the current study could be interpreted in the light of kinematic adaptations to running with shoes with differing stiffness. For instance, one experimental study indeed showed a tendency towards a higher knee flexion velocity immediately following touchdown when running with harder shoes (Clarke et al., 1983). However, as indicated in the introduction, no general picture exists about how subjects modify their running style as a function of shoe stiffness. Additionally, the barefoot condition differs also in other mechanical aspects such as the geometry of the foot-ground interface. Therefore, the interpretation of the barefoot running results towards adaptations expected in running with harder shoes is not straightforward.

Based on our data and on the findings of Wright et al. (1998), the following working hypothesis can be put forward: in response to changing cushioning properties of the foot-ground interface, the active initiation of the kinematic adaptations just before foot contact, is followed by a more passive kinetic interaction between the contacting leg and the ground, during the initial ground contact phase. This will be the topic of future research.

4.2. General sagittal plane kinematics

During the initial ground contact phase (Figs. 4A and B) the support leg changes from a more extended (at touchdown) to a more flexed configuration in shod running, compared to barefoot running. Attention must be paid to the instant represented by Fig. 4B: the impact peak occurs significantly later for shod running (33 versus 11 ms in barefoot running). Anyway, the more flexed knee position in shod running continues throughout midstance (see Figs. 4B and C) resulting in a larger maximal knee flexion in the shod condition (see Table 3). Towards the end of the stance phase at push-off, kinematic differences between both conditions disappear.

The external forces are non-different during midstance (absolute F_{za}). This implies the overall stiffness of the support leg to be higher during barefoot running. The ratio of the maximal vertical ground reaction force (F_{za}) to the leg compression (from touchdown till the end of midstance) can be taken as a measure for overall leg stiffness during stance phase in locomotion (Ferris et al., 1998) and indeed displays significantly higher values for the barefoot condition (K_{leg}: see Table 3).

Ferris and co-workers (1998) showed that runners adjust their leg stiffness to accommodate for rather large changes in surface stiffness. In that way, their subjects kept their overall vertical stiffness — i.e. f_{za} divided by vertical displacement of the centre of gravity from touchdown to the end of midstance — constant, resulting in similar general running mechanics. For instance, ground contact time and stride frequency remain the same on different surfaces. A less compliant surface was compensated by a lower leg stiffness en vice-versa. However, in the current experiments the foot–ground interface is less compliant in the barefoot running condition (see the smaller ankle displacement), but the overall leg stiffness during stance phase is higher compared to shod running. This presumes that there is no equivalent compensation towards a constant vertical stiffness, which can be inferred from the significantly smaller foot contact time in barefoot running (see Table 2). The higher step frequency relates significantly to the latter (correlation between step frequency and contact time: bare: $r = -0.6$, $p < 0.05$; shod: $r = -0.6$, $p < 0.05$). The horizontal distance travelled through the stance phase is smaller in barefoot running and explains to a large extent the reduction in step length (correlation between step length and horizontal distance: bare: $r = 0.7$, $p < 0.05$; shod: $r = 0.67$, $p < 0.05$). On the other hand, the flight phase remains unaffected: distance and duration of the airborne phase do not differ in both conditions. It is clear that the higher step frequency in barefoot running relates to kinematic alterations during the stance phase. So, when subjects run barefoot, runners do not maintain similar running mechanics, which contrasts to the findings of Ferris et al. (1998) for running on different resilient materials. This points towards (an)other functional demand(s) in barefoot running. The adaptations in stride kinematics to barefoot running are primarily due to changes in touchdown geometry and the subsequent joint movements during initial ground contact. As discussed above, the most prominent difference between both conditions is the much flatter foot placement at touchdown, realized by a larger plantar flexion and by more knee flexion. This causes the heel to be placed closer to the vertical projection of the hip (difference — shod minus bare — in horizontal distance from the vertical projection of the hip to the heel: at 3.5 m s^{-1}: 3 cm; at 4.5 m s^{-1}: 4 cm; at 5.5 m s^{-1}: 5 cm) and explains to a large extent the reduction in the horizontal distance travelled through the stance phase (correlation between horizontal distance covered during stance and the horizontal distance of the hip to the heel: bare: $r = 0.77$, $p < 0.05$; shod: $r = 0.88$, $p < 0.05$).

Again, it should be stressed that these gross kinematic adaptations between conditions are found in the same way for all subjects at the three tested velocities.

4.3. Inter-subject variability

The high consistency between the runners in sagittal plane kinematics cannot be found for the foot and ankle movements in the frontal plane. The foot touches the ground less inverted in barefoot running, but it was not observed on all subjects. With the exception of $\Delta\gamma_{imp}$, significant interaction effects between condition and subjects were found for all frontal plane kinematic variables, making it difficult to draw conclusions for the whole test group (see Fig. 6 with as an example the maximal subtalar eversion). This lack of consistency cannot be explained by the results of the current study, probably because of the use of a two-dimensional technique which

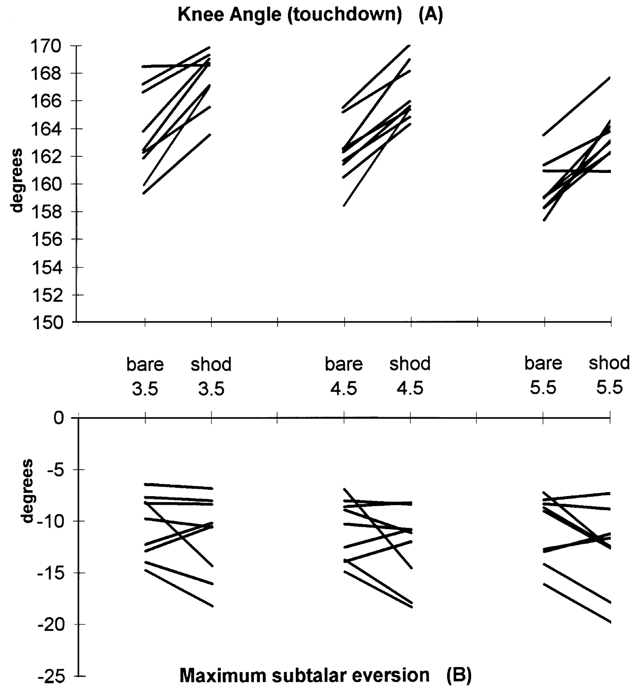

Fig. 6. Individual average values of the 9 runners, barefoot and shod at three velocities. (A) knee angle at touchdown; (B) maximum subtalar eversion. The interaction effect (subject × condition) is larger for the the frontal plane kinematics.

does not give information about longitudinal rotation of the leg segments. A hypothesis could be that the frontal plane kinematics are influenced by the individual anatomy of the foot–ankle. This should be further investigated taking inter-individual differences in foot–ankle anatomy into account.

5. Conclusion

In conclusion, this study shows a change in running pattern between barefoot and shod running, mainly characterized by a larger external loading rate and a significantly flatter foot placement at touchdown in barefoot running. The joint configuration of the leg is already prepared in free flight by a larger plantar flexion, by more knee flexion and a larger knee flexion velocity while running barefoot, implying an actively induced adaptation strategy for this running condition. Plantar pressure measurements in the barefoot condition show a correlation ($r = -0.7$, $p < 0.05$) between a flatter foot placement and lower peak heel pressures. Therefore, it is assumed that runners adopt a flatter foot placement in barefoot running in an attempt to limit the local pressure underneath the heel.

The observed adaptations in stride kinematics for barefoot running — shorter step length and larger step frequency — were primarily due to changes in touchdown geometry. Throughout the stance phase, leg stiffness is higher in barefoot running favoring a higher step frequency. All sagittal kinematic adaptations between conditions were in the same way for all subjects at the three tested running velocities. This is in contrast with the prominent interaction effects between subjects and conditions in the frontal plane kinematics, meaning that there is no uniform adaptation strategy for all runners concerning the rearfoot kinematics.

Future research should include a three-dimensional analysis, to study longitudinal rotation of the leg segments, and a detailed anatomical evaluation of the foot–ankle complex. Both methodological changes will improve the understanding of the inter-subject variability concerning rearfoot kinematics.

Acknowledgements

This research was partially financially supported by a grant of BOZF-RUG (nr 011B0996). Special thanks to an anonymous reviewer for his valuable suggestions.

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