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Original Article

Differences in vertical ground reaction forces during first attempt of barefoot running in habitual shod runners

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Abstract
Many suggest that switching from shod running to barefoot running decreases injury risk and makes running more natural. Scientists have reported biomechanical differences in shod and barefoot running, with a number of differences related to increased injury risk. Our research is focused on investigating the acute differences when switching to barefoot running for the first time. Twenty long distance runners were subjected to an experiment as part of this research. The subjects ran 5 trials across two force plates both in shod and barefoot conditions. The ground reaction force (GRF) was recorded for each subject. The stance time, the initial impact loading rate (LR), the impact maximum (IM), the time when the IM was reached, the thrust maximum, the average vertical GRF, and the decay rate (DR) were calculated from the obtained GRF. The results show that the mean LR and DR were greater by 42.191 BW/s ($p=0.006$) and 5.922 BW/s ($p<0.001$) respectively in barefoot running compared to shod running. The mean stance time and the time to IM was greater by 10.15 ms ($p=0.013$) and 5.00 ms ($p=0.017$) respectively in shod running compared to barefoot running. IM and LR had a significant correlation in shod running condition only ($r=0.842$, $p<0.001$). Both conditions, however, had significant correlation between LR and time to IM (shod: $r=-0.646$, $p=0.002$; Bare: $r=-0.741$, $p<0.001$). According to our data, the responses of the subjects to barefoot running were not unambiguous and in some cases not less traumatic.
Key Words: Running, Barefoot, First impact, Ground reaction force

Introduction

Barefoot running is not a new concept, but it has become a popular research topic in recent years (Kaplan, 2014). Thereby it has become also a hot discussion topic among researchers, coaches, and runners. A lot of studies in recent years have been created on barefoot effects on running economy (Hanson et al., 2011), avoiding injuries (Lieberman, 2012) or that it may be a running skill (Tam et al., 2014) and an acceptable training method for coaches who can understand and minimize the risks of barefoot running (Jenkins & Cauthon, 2011). Separate studies are showing different benefits of barefoot running (Williams et al., 2012), but authors of reviews are more cautious about claiming potential benefits or the opposite (Rothschild, 2012). Some authors are emphasizing that there is a lack of high-quality evidence and no conclusions can be made on benefits or risks while running barefoot, in minimalist shoes or shod (Perkins et al., 2014).

Scientists have reported of shorter step and stride lengths, and higher stride frequencies when running barefoot (De Wit et al., 2000a; Divert et al., 2005; Bonacci et al. 2013). Contact time and stride duration reduce in barefoot running compared to shod (McCallion et al., 2014). Loading rate in vertical ground reaction force during initial contact has been a focus since early barefoot running studies. Some researchers found a reduction in loading rate (LR) in habitual barefoot runners who land on their forefoot (Divert et al., 2005; Lieberman et al., 2010). Other research shows that there is an increase in initial loading rate when switching from shod running to barefoot running (Tam et al. 2017).

Material & methods

Twenty long distance male shod runners participated in this study (Age: 25.9 (4.5) years, weight: 69.4 (7.1) kg, height: 181.7 (7.7) cm; Mean (SD)). Subjects were able to run half-marathon in less than 80 min and were injury free for six months before the study. All participants signed a subject consent approved by the ethics committee.

Running trails were conducted on a 30 m long wooden running surface (leveled at the same height as force plates). Runners performed 5 successful running trials (appropriate running velocity and accurate step on force plates). Running velocity was set based on their current half-marathon performance pace and it was from 15.7 to 18.9 km/h with mean of 17.84 km/h (SD 0.96).

Data were collected using two synchronized force platforms (BTS P-6000, Italy), sampling at 1000 Hz. The sensitive area of one force plate was 60 x 40 cm, minimum height – 5.7 cm. Runners performed one

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successful running step over the force plates. Length between force plates was adjusted according to each runner individual step length at given running velocity. While running over the plates, one foot was placed on the first plate, and other on the second plate. Runners were instructed not to change their step length in any way while running over the plates. They could choose freely which leg touches the first force plate. In each trial both legs vertical ground reaction force (vGRF) data were collected. After first five trials participants had to take off their running shoes and repeat 5 more clean running trials at the same velocity, only barefoot. For each participant one clean stance phase from each of the legs was analyzed.

Running velocity was calculated from 10 m distance travel time. Time was measured with 3 synchronized photocells (Microgate Polifemo Light Radio, Italy) positioned 5 m from each other (Figure 1). The trial was confirmed as successful if it is clean by visual and laser velocity detection – when it did not differ more than 5% of the target speed, and when it was clean both feet contact with force platforms.

All force platform data were filtered using a Butterworth 4th order low-pass filter with 50Hz cut-off frequency.

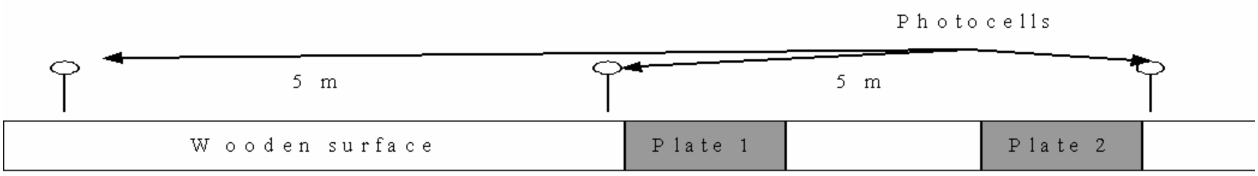

Fig.1. Placement of wooden surface, force plates and photocells

Stance Time (ST), initial impact Loading Rate (LR), Impact Maximum (IM), a time when IM was reached (IMt), Thrust Maximum (TM), Average vGRF (AvGRF) and Decay Rate (DR) were calculated for both running patterns (shod and barefoot). LR was calculated between 20% and 80% of initial impact peak of vGRF when present (Laughton et al., 2003; Kluitenberg et al., 2012) or to 13% of stance time when initial impact peak absent (Boyer et al., 2014). Impact peak was defined as the first peak within the first 50 ms of stance (Nigg et al. 1995). Stance time was defined between first ground contact (vGRF > 20 N) and takeoff (vGRF < 20 N) (Nordin et al., 2015). Thrust Maximum was defined as the last vGRF maximum from which it starts to decrease. Decay Rate was calculated after TM and between 1 BW + 50 N and 50 N (Munro et al., 1987).

To check data normality Shapiro-Wilk test was used. Differences between barefoot and shod data were compared using Student's t-test or non-parametric Wilcoxon signed-rank test, and 95% confidence interval (CI) was calculated. Correlation between groups was compared using Pearson's correlation.

All data were processed and calculated using a custom written script in R 3.4.3 (R Core Team, 2017) and shown as the mean ± standard deviation (SD) if not stated otherwise.

Results

Summary of individual changes in vGRF variables and descriptive statistics is given in Table 2, Figure 2 and Figure 3. Participants mean ST running with shoes was greater than running barefoot by 10.15 ms (Shod: 183.700 ± 14.804 ms, Bare: 173.550 ± 9.462 ms, $p = 0.013$, Table 1). LR and DR was greater when running barefoot 43.191 BW/s and 5.922 BW/s respectively (LR, bare: 197.916 ± 78.573 BW/s, LR, shod: 154.724 ± 64.195 BW/s, $p=0.006$; DR, bare: 36.299 ± 6.769 BW/s, DR, shod: 30.378 ± 3.779 BW/s, $p<0.001$, Table 1). IMt was shorter on average by 5 ms when running barefoot (Shod: 24.2 ± 6.2 ms, Bare: 19.9 ± 7.8 ms, $p=0.017$, Table 1). There were no significant difference in IM ($p=0.720$), TM ($p=0.430$) and AvGRF ($p=0.277$)

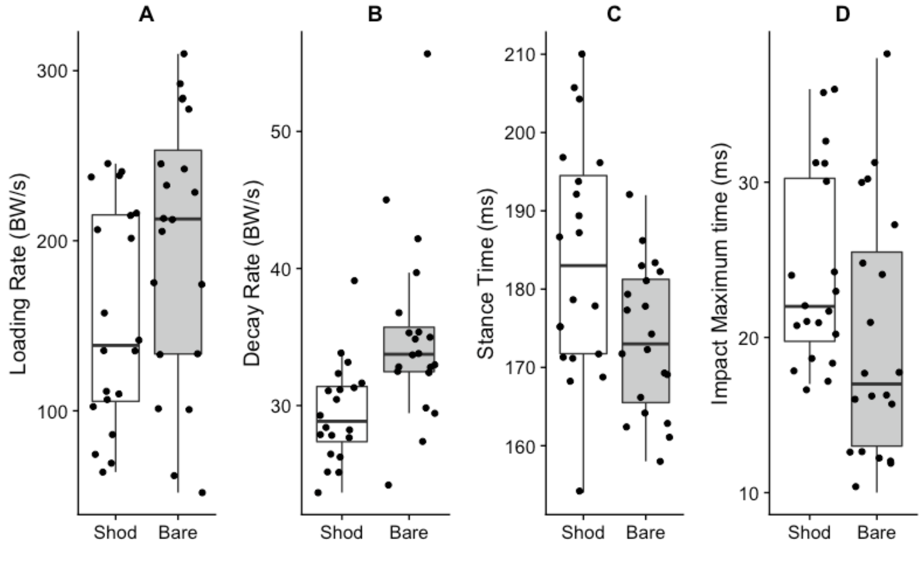

Fig.2. Variability between participants of (A) loading rate, (B) decay rate, (C) stance time and (D) time to impact maximum.

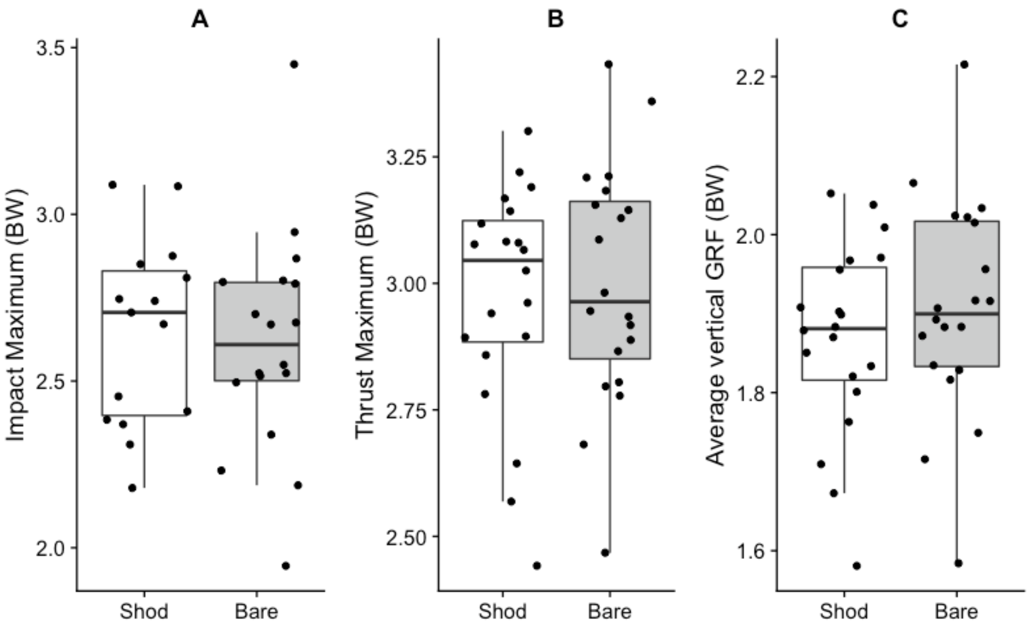

Fig.3. Variability between participants of (A) Impact maximum, (B) thrust maximum and (C) average ground reaction force.

Groups mean LR increase when switching from shod to barefoot was 35.08%, and it ranged between 52.81% decrease to 174.27% increase. DR mean increase was 8.03%, and it ranged between 21.10% decrease to 30.01% increase. ST when switching from shod to barefoot decreased in average was 5.09% and it ranged between 19.52% decrease to 9.74% increase. IMt mean decrease was 16.8% and it ranged between 58.1% decrease to a 31.6% increase. There were no low correlation (r=0.409, p=0.018, Figure 4) between IM and LR when comparing shod and barefoot runners as a whole group, but shod runners had high correlation between IM and LR (r=0.842, p<0.001, Figure 4), instead of barefoot runners who had no significant correlation (r=0.190, p=0.450, Figure 4). There were moderate correlation in all groups between LR and IMt (Shod: r=-0.646, p=0.002; Bare: r=-0.741, p<0.001; All data: r=-0.730, p<0.001), but only shod runners had significant correlation between IM and IMt (r=-0.748, p=0.001).

Table 1. Statistical comparison of barefoot vs. shod running condition.

	Mean difference	**95% CI**	**p-value**
Impact Maximum (BW)	-0.033	(-0.221; 0.147)	0.720
Loading Rate (BW/s)	43.191	(11.770; 71.711)	0.006
Thrust Maximum (BW)	0.026	(-0.079; 0.125)	0.430
Decay Rate (BW/s)	5.922	(3.192; 6.533)	<0.001
Average vGRF (BW)	0.038	(-0.034; 0.110)	0.277
Stance Time (ms)	-10.15	(-18.00; -4.50)	0.013
IMt (ms)	-5.00	(-8.50; -1.00)	0.017

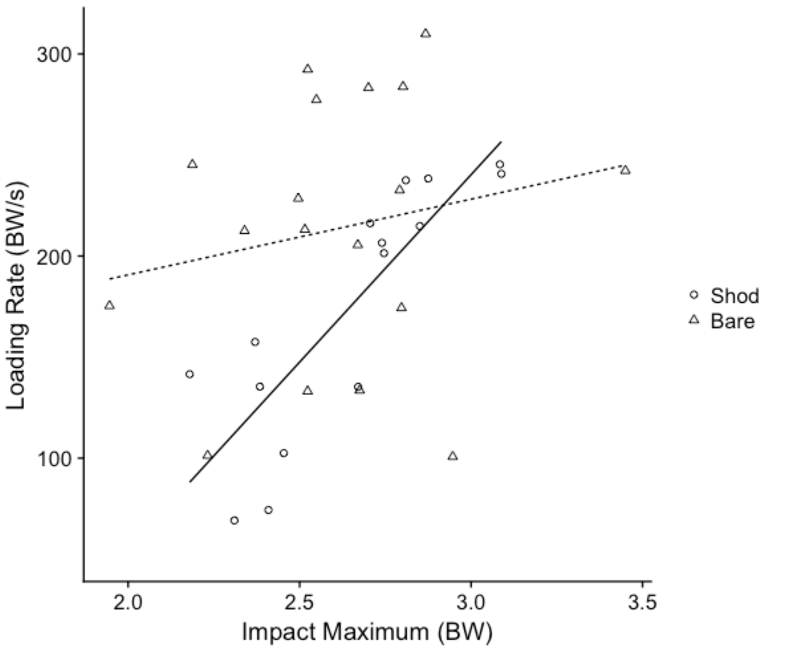

Fig.4. Relationship between impact maximum with initial loading rate.

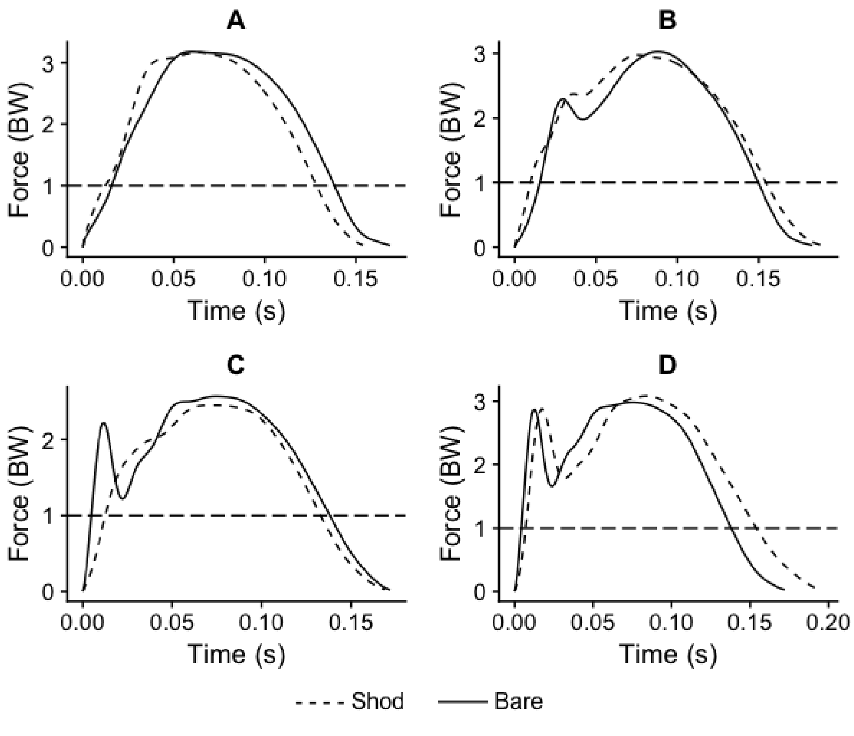

Fig.5. Different vGRF patterns. (A) shod - forefoot, bare - forefoot, (B) shod - midfoot, bare - rearfoot, (C) shod - forefoot, bare - rearfoot, (D) shod - rearfoot, bare - rearfoot.

Four different changes in foot strike patterns were observed. Most common (11 participants) pattern was a rearfoot strike and after switching to barefoot it didn't change (Fig. 5D). 4 participants who were running midfoot when started running barefoot changed their foot strike pattern to rear foot (Fig 5B). Forefoot strike runners, when switched to barefoot, changed their pattern to rear foot (Fig. 5C) or didn't change running and continued running forefoot (Fig. 5A).

Table 2. Results of all participants. ST - stance time, LR - loading rate, IM - impact maximum, TM - thrust maximum, AvGRF - average ground reaction force, DR - decay rate, IMt - time to impact peak. SH - shod running. BF - barefoot running

Part.	ST (ms)		LR (BW/s)		IM (BW)		IMt (ms)		TM (BW)		AvGRF (BW)		DR (BW/s)	
	SH	BF	SH	BF	SH	BF	SH	BF	SH	BF	SH	BF	SH	BF
R1	172	163	240.660	242.230	3.088	3.450	19	25	3.083	3.086	1.956	1.917	27.774	30.253
R2	189	183	69.200	101.286	2.310	2.232	36	30	2.846	2.946	1.834	1.749	25.627	31.010
R3	178	164	201.424	277.329	2.746	2.549	21	10	3.301	3.145	1.971	2.034	30.013	31.140
R4	210	169	135.281	283.791	2.671	2.802	31	13	2.644	2.797	1.673	1.916	22.406	29.131
R5	197	178	135.375	175.348	2.384	1.946	30	16	3.078	2.888	1.870	1.872	28.498	29.772
R6	192	182	102.475	174.328	2.454	2.797	33	31	2.569	2.777	1.710	1.835	21.956	25.480
R7	204	174	157.480	133.111	2.370	2.523	31	27	3.142	3.360	1.801	2.015	28.057	32.943
R8	154	169	63.962	61.830	-	-	-	-	3.118	3.129	1.967	1.892	34.261	28.709
R9	171	181	245.349	213.137	3.084	2.515	18	18	3.024	2.682	2.009	1.829	28.808	22.730
R10	175	166	214.866	283.265	2.850	2.701	22	12	2.893	2.935	1.851	1.883	30.448	31.220
R11	194	183	74.346	100.734	2.409	2.947	36	38	2.962	3.209	1.821	1.883	28.483	30.566
R12	187	177	216.221	232.610	2.706	2.792	18	18	2.940	3.155	1.899	2.022	25.790	30.335
R13	168	162	206.517	228.487	2.740	2.496	21	16	3.219	2.805	2.052	1.816	33.189	31.520
R14	179	179	85.997	133.542	-	2.675	-	30	2.859	3.433	1.879	2.065	35.294	34.328
R15	187	158	111.473	205.515	-	2.670	-	16	3.190	3.183	1.902	2.215	31.310	39.300
R16	175	186	109.918	51.867	-	-	-	-	3.066	2.866	1.908	1.716	29.198	28.659
R17	196	172	238.344	309.914	2.875	2.867	17	13	3.080	2.981	1.883	1.956	27.496	30.736
R18	206	192	141.534	245.191	2.179	2.187	24	12	2.442	2.467	1.581	1.584	20.014	22.637
R19	171	161	237.486	212.470	2.810	2.339	17	16	3.168	3.212	2.038	2.024	28.539	35.690
R20	169	172	106.582	292.327	-	2.524	-	12	2.781	2.917	1.763	1.907	29.273	30.071
-MN	183.7	173.6	154.724	197.916	2.645	2.612	24.2	19.9	2.973	2.999	1.868	1.907	30.378	36.299
-SD	14.8	9.5	64.195	78.573	0.280	0.333	6.2	7.8	0.226	0.267	0.121	0.139	3.779	6.769
-MD	183	173	138.454	212.804	2.706	2.609	22	17	3.045	2.964	1.881	1.900	30.033	35.341
-CV	8.06	4.45	41.490	39.70	10.60	12.74	25.6	39.4	7.59	7.90	6.50	7.27	12.44	18.65

Discussion

Results of this study show that LR on average is significantly increased when switching from shod running to barefoot running which may increase the risk of injury (Zadpoor & Nikooyan, 2011). Our finding coincides with others studies which showed that shod runners on first barefoot attempt may not lower their loading rates (Cheung & Rainbow, 2014; Tam et al., 2017). The observed decrease in stance time also coincides with other studies (De Wit et al., 2000a; Divert et al., 2005; Bonacci et al. 2013). Similar to our findings Knoepfli-Lenzin et al. reported higher loading rate and decay rate in barefoot runners than shod runners which are explained by sole thickness affecting the rate of force development (Knoepfli-Lenzin et al., 2014).

Nigg reported that there is a high relationship between LR and IM (Nigg, 1983), but our results show that high correlation is only in shod runners group. LR and IM do not correlate in the first attempt of barefoot running. LR increase can be explained by a shorter time when IM is reached instead of IM increase (Wakeling et al., 2003; De Wit et al., 2000b). In this research, we tried to add some evidence by measuring the acute effects of switching from shod to barefoot running. There are runners using barefoot running for their training (Squadrone & Gallozzi, 2009). In our research, none of the runners used barefoot running for serious training purposes. None of them was prepared to run barefoot in this research. So the group was equal according to these conditions. Allegations like “switch to injury-free running” or “barefoot running are the natural form of running” can be heard often. According to our data, these allegations (1) doesn’t work for everybody the same way; (2) the acute effect can happen to be not very “injury free” but more likely - increase the risk of injuries; (3) there are some biomechanical characteristics that changed after switching to barefoot but it is definitely not a different form (or natural) of running. It is still running. Our evidence doesn't support allegations like these (or similar). Certainly, we didn't test runners after a longer period or adaptation of barefoot running.

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