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Original article

Can minimal running shoes imitate barefoot heel-toe running patterns? A comparison of lower leg kinematics

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Abstract

Background: Numerous studies about the interaction between footwear (and barefoot) and kinematic and kinetic outcomes have been published over the last few years. Recent studies however lead to the conclusion that the assumed interactions depend mainly on the subjects' experience of barefoot (BF) walking/running, the preferred running strike pattern, the speed, the hardness of the surface, the thickness of the midsole material, and the runners' level of ability. The aim of the present study was to investigate lower leg kinematics of BF running and running in minimal running shoes (MRS) to assess comparability of BF kinematics in both conditions. To systematically compare both conditions we monitored the influencing variables described above in our measurement setup. We hypothesized that running in MRS does not alter lower leg kinematics compared to BF running.

Methods: Thirty-seven subjects, injury-free and active in sports, ran BF on an EVA foam runway, and also ran shod wearing Nike Free 3.0 on a tartan indoor track. Lower-leg 3D kinematics was measured to quantify rearfoot and ankle movements. Skin markers were used in both shod and BF running.

Results: All runners revealed rearfoot strike pattern when running barefoot. Differences between BF and MRS running occurred particularly during the initial stance phase of running, both in the sagittal and the frontal planes. BF running revealed a flatter foot placement, a more plantar flexed ankle joint and less inverted rearfoot at touchdown compared to MRS running.

Conclusion: BF running does not change the landing automatically to forefoot running, especially after a systematic exclusion of surface and other influencing factors. The Nike Free 3.0 mimics some BF features. Nevertheless, changes in design of the Nike Free should be considered in order to mimic BF movement even more closely.

Keywords: 3D-kinematics; Ankle; Barefoot; Minimal running shoes; Rearfoot; Running

1. Introduction

Advantages and disadvantages of barefoot (BF) running have been of major interest for numerous years, scientifically as well as in the running population. As a consequence of this, there have been numerous concepts and products on the market that mimic specific aspects of BF movement, shape, or feeling, "suggesting that some of the perceived advantages of barefoot running are transferred into a shod condition".[1] Scientifically, publications and discussions about advantages and disadvantages of BF running increased tremendously after a publication by Lieberman et al.[2] in *Nature*.

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Numerous studies about the interaction between shod and BF kinematic and kinetic outcomes have been published over the last few years and described by Nigg[1] and Nigg and Enders.[3] Most of these studies were based on the comparison of running in traditional running shoes (TRS) and BF running. Recent studies however lead to the conclusion that the assumed interactions depend mainly on the subjects' experience with BF walking/running,[2,4–8] the preferred running strike pattern,[9,10] the speed,[11] the hardness of the surface,[12] the thickness of the midsole material,[13] and the runners' level.[10] A few studies[4–7] have already included minimal running shoes (MRS) into their setup.

To systematically analyze suggested "barefoot features" in given MRS and compare with the BF situation, it is necessary to take the above-mentioned criteria into account. Therefore, studies should monitor the subjects' experience in BF walking/running (unexperienced or experienced), the preferred running strike pattern (rearfoot, midfoot, forefoot), the running speed (typical running speed, depending on runners' level and gender), the hardness of surface (hardness of BF running surface comparable to midsole hardness of MRS), the thickness of midsole material (one thickness) and the subject's athletic level (recreational, elite). Further, skin mounted markers should be used[14] as shoe-mounted markers are not adequate to assess the in-shoe foot motion, and consequently overestimate its real motion. Although these results have been shown for TRS with stiff heel counters, the flexible heel counter of MRS might have an even greater influence on the resultant rearfoot and ankle kinematics.

The aim of the present study was to investigate lower leg kinematics of BF running and running in MRS (Nike Free 3.0; Nike Inc., Beaverton, OR, USA) to assess comparability of BF kinematics in both conditions. Furthermore, we aimed to find out if foot strike characteristics remained the same after monitoring the influencing variables described above in our measurement setup. We hypothesized that running in MRS does not alter lower leg kinematics compared to BF running and that foot strike pattern remained the same in both conditions.

2. Materials and methods

2.1. Subjects

Overall, 37 subjects were included in the study (Table 1). All subjects were rearfoot strikers (visually inspected beforehand while running in their own TRS), free of any injury for at least 6 months prior to the study, recreational athletes (different sports) and aged between 18 and 55 years. None of the subjects had a history of or experience with BF running. The study complies with the Declaration of Helsinki, and all subjects signed a written consent form prior to the testing procedures.

2.2. Experimental setup

Three-dimensional kinematics was recorded with a six-camera infrared system (ViconPeak, MCam, M1; Oxford, UK) at a sampling frequency of 250 Hz. All runners ran BF on a 20-m EVA foam runway (shore hardness approx. 40), and shod wearing Nike Free 3.0 (shore hardness approx. 40) on a 20-m tartan indoor track. The height of the foam runway was 10 mm, comparable to the midsole/outsole heel height of MRS. The order of running conditions was randomized. Prior to the recorded measurements, sufficient time was allowed for the subjects to familiarize themselves with the laboratory setup and to get used to the running speed and surface to enable an individual running style. All subjects ran with a controlled running speed of 11 km/h monitored using a photoelectric barrier, and a running speed between 10.5 km/h and 11.5 km/h was accepted. The test speed of 11 km/h was chosen as this is an average running speed in recreational athletes, both for men and women. Touch-down was visually inspected to find out if subjects landed on the rearfoot or on the mid/forefoot.

Eighteen markers were placed on each subject according to the recommendations of the International Society of Biomechanics,[15] marking both shanks (medial and lateral tibia plateau, tibial tuberosity, medial tibial crest, lateral and medial malleoli), the foot (lateral, medial, and posterior calcaneus), and the hallux. Rearfoot markers were screwed to a short thread (∼1 cm) and screw sockets were attached to customized flexible plastic disks placed on the calcaneus to ensure their visibility and identical placement for both BF and shod conditions (Fig. 1) and to ensure a good fit of the markers with respect to the foot. Joint excursions were quantified by calculating Cardan angles according to Söderkvist and Wedin[16] with the foot segment rotating with respect to the shank segment (ankle dorsiflexion/plantarflexion, rearfoot inversion/eversion), or with respect to the global coordinate system (tibial rotation, sagittal ankle, and frontal rearfoot motion). Further, the first rotation was computed around the sagittal axis (dorsiflexion/plantarflexion), the second rotation around the frontal axis (inversion/eversion) and finally, the third rotation was computed around the transversal axis (external/internal rotation). For

Table 1
Overview of all subjects included in the study (mean ± SD).

Subject	n	Age (year)	BMI (kg/m^2)	Weight (kg)	Height (cm)	Running (h/week)	Exercising (h/week)
All	37	30 ± 9	22 ± 2	67 ± 12	175 ± 9	1 ± 2	5 ± 4
Male	14	26 ± 5	24 ± 2	78 ± 11	181 ± 7	1 ± 2	5 ± 4
Female	23	32 ± 11	21 ± 2	61 ± 6	170 ± 7	1 ± 1	6 ± 4

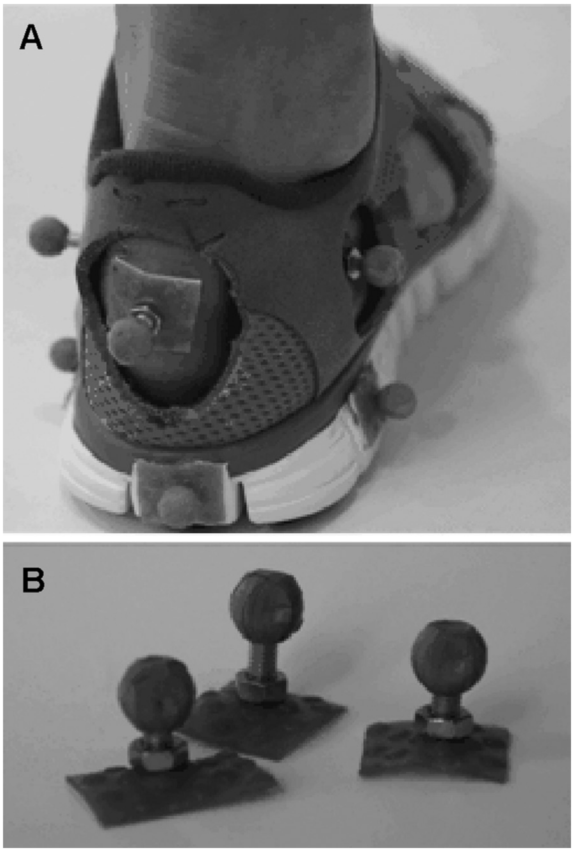

Fig. 1. Placement of skin-mounted markers on the rearfoot and of external shoe markers (A). Skin-mounted markers for the rearfoot segment (B).

the subsequent analysis, stance phase was detected according to Maiwald et al.[17] and subsequently normalized to 100 data points which equal 100% of stance phase (%SP); swing phase was neglected. Mean joint excursion curves and discrete variables were based on 10 valid trials for each subject.

The following joint motions were calculated: tibial external/internal rotation (TER, TIR), ankle dorsiflexion/plantarflexion (ADF, APF), rearfoot inversion/eversion (RFIN, RFEV) as well as frontal rearfoot (RFGIN, RFGEV) and sagittal ankle motion (ASAG) with respect to the global coordinate system, respectively.

Discrete variables were:

- Initial joint excursion at touchdown (°) for tibial external rotation (TER_{init}), ankle dorsiflexion (ADF_{init}), rearfoot inversion ($RFIN_{init}$), frontal rearfoot motion ($RFGIN_{init}$), and sagittal ankle motion ($ASAG_{init}$);
- Maximal joint excursions (°) and timing (%SP) for tibial internal rotation (TIR_{max}, t TIR_{max}), ankle dorsiflexion (ADF_{max}, t ADF_{max}), rearfoot eversion ($RFEV_{max}$, t $RFEV_{max}$), and frontal rearfoot motion ($RFGEV_{max}$, t $RFGEV_{max}$);
- Maximal joint excursions (°) for tibial external rotation (TER_{max}), ankle plantarflexion (APF_{max}), rearfoot inversion ($RFIN_{max}$), and frontal rearfoot motion ($RFGIN_{max}$);
- Ranges of motion (°) for internal and external tibial rotation (TIR_{ROM}, TER_{ROM}), ankle dorsi/plantarflexion (ADF_{ROM}, APF_{ROM}), rearfoot eversion/inversion (RFEV-ROM, RFINROM), and frontal rearfoot motion ($RFGEV_{ROM}$, $RFGIN_{ROM}$).

2.3. Shoes

Nike Free 3.0 served as test shoe in sizes US6 (24 cm) − US12 (30 cm). To record the markers placed directly on the rearfoot, three small windows (lateral, medial, and posterior) were cut into the heel counter (Fig. 1). Three markers were placed on the sole around the heel (lateral, medial, and posterior) to determine touchdown, and one marker was located on the tip of the shoe to calculate toe-off. Nike Free 3.0 was chosen as MRS due to the following proposed "barefoot features": extreme flexibility of complete midsole and outsole in running and medio-lateral direction, alignment of midsole/outsole squares adjusted to center of pressure path in BF running, low midsole height and flexible textile upper material (whole upper material, no stiff heel counter).

2.4. Statistical analysis

The analysis of kinematic data was based on a randomized side for each subject to avoid bias, such as dominant *vs.* non-dominant leg if only one side were consistently evaluated. A comparison of dominant or non-dominant leg only was not applicable as not all subjects were able to define which side was dominant. Thus, 18 right and 19 left sides were included in the subsequent analysis. Continuous means of 10 trials and 95% confidence intervals (CI) were computed for both conditions and for each joint motion to present kinematic data. Non-overlapping CI indicates a significant difference between BF and MRS conditions.

Group means, standard deviations (SD), medians and the upper and lower limits of the 95%CI were calculated, dependent *t* tests were conducted to analyze differences between BF and MRS conditions. The level of significance was set at $\alpha = 0.05$. Since 25 variables were analyzed, 25 *t* tests were performed and the test level was adjusted according to the Bonferroni procedure[18] to $p < 0.002$ ($0.05/25 = 0.002$). Statistical analyses were carried out using JMP (version 10, SAS Institute Inc., Cary, NC, USA).

3. Results

All participants revealed the same foot strike pattern in BF and MRS. The results of lower leg kinematics of BF running and running in MRS (Nike Free 3.0) to assess comparability of BF kinematics in both conditions are shown in Table 2 and Fig. 2. For transversal tibia motion, running in MRS showed a later t TIR_{max} and a decreased TER_{max} compared to BF. With regard to sagittal ankle movement, MRS was accompanied by greater ADF_{init} and ADF_{max} as well as a later t ADF_{max}. The greater APF_{ROM} for MRS was derived subsequently from the differences in ADF_{max} and equal amounts of APF_{max}. Frontal

Table 2
Three dimensional lower leg kinematics for running barefoot (BF) and shod, wearing minimal running shoes (MRS). Displayed are group means ± SD, group medians, upper and lower limits of the 95% confidence intervals (CI).

	BF				MRS			
	Mean ± SD	Median	95%CI up	95%CI low	Mean ± SD	Median	95%CI up	95%CI low
TER_{init} (°)	3 ± 6	1	5	0	1 ± 5	0	3	0
TIR_{max} (°)	−5 ± 5	−5	−4	−7	−5 ± 5	−5	−4	−7
t TIR_{max}* (%SP)	46 ± 19	46	49	42	53 ± 11	55	56	49
TER_{max}* (°)	7 ± 7	6	9	5	5 ± 6	4	7	3
TIR_{ROM} (°)	8 ± 3	8	9	7	7 ± 3	6	8	6
TER_{ROM}* (°)	12 ± 5	12	14	11	10 ± 5	9	12	9
ADF_{init}* (°)	1 ± 6	2	3	−1	6 ± 6	7	8	4
ADF_{max}* (°)	12 ± 4	12	13	11	15 ± 3	14	16	14
t ADF_{max}* (%SP)	43 ± 3	43	44	42	45 ± 4	45	47	44
APF_{max} (°)	−30 ± 6	−30	−28	−32	−31 ± 5	−30	−29	−32
ADF_{ROM} (°)	11 ± 4	12	12	10	11 ± 3	11	12	10
APF_{ROM}* (°)	42 ± 5	42	43	40	45 ± 5	45	47	44
$RFIN_{init}$* (°)	6 ± 3	6	6	5	9 ± 3	8	9	7
$RFEV_{max}$ (°)	−4 ± 3	−3	−3	−5	−4 ± 3	−4	−3	−5
t $RFEV_{max}$* (%SP)	33 ± 7	33	35	31	38 ± 7	40	41	36
$RFIN_{max}$ (°)	6 ± 3	6	7	5	5 ± 3	5	6	4
$RFEV_{ROM}$* (°)	10 ± 3	10	11	9	12 ± 3	12	12	11
$RFIN_{ROM}$ (°)	10 ± 3	10	11	9	9 ± 3	9	10	8
$RFGIN_{init}$ (°)	10 ± 3	10	11	9	11 ± 3	11	12	10
$RFGEV_{max}$ (°)	−1 ± 3	−1	9	−2	0 ± 3	0	1	−1
t $RFGEV_{max}$* (%SP)	34 ± 7	35	36	31	39 ± 7	40	42	37
$RFGIN_{max}$ (°)	15 ± 6	15	17	14	14 ± 6	14	16	12
$RFGEV_{ROM}$ (°)	11 ± 3	11	12	10	12 ± 3	12	13	11
$RFGIN_{ROM}$* (°)	16 ± 5	16	18	14	14 ± 5	13	16	13
$ASAG_{init}$* (°)	13 ± 5	14	15	11	22 ± 6	21	24	20

Notes: Initial joint excursion (°) at touch-down for tibial external rotation (TER_{init}), ankle dorsiflexion (ADF_{init}), rearfoot inversion ($RFIN_{init}$), global frontal rearfoot ($RFGIN_{init}$), and global sagittal ankle ($ASAG_{init}$) motion. Maximal joint excursion (°) and its timing (%SP) for tibial internal rotation (TIR_{max}, t TIR_{max}), ankle dorsiflexion (ADF_{max}, t ADF_{max}), rearfoot eversion ($RFEV_{max}$, t $RFEV_{max}$), and global rearfoot eversion ($RFGEV_{max}$, t $RFGEV_{max}$). Maximal joint excursion (°) for tibial external rotation (TER_{max}), ankle plantarflexion (APF_{max}), rearfoot inversion ($RFIN_{max}$) global rearfoot inversion ($RFGIN_{max}$). Range of motions (°) for tibial internal and external rotation (TIR_{ROM}, TER_{ROM}), ankle dorsiflexion and plantarflexion (ADF_{ROM}, APF_{ROM}), rearfoot eversion and inversion ($RFEV_{ROM}$, $RFIN_{ROM}$) and global rearfoot eversion and inversion ($RFGEV_{ROM}$, $RFGIN_{ROM}$). Statistical significance (*) is reported for $p < 0.002$ (0.05/25).

rearfoot kinematics revealed a more inverted rearfoot at touchdown ($RFIN_{init}$), a later t $RFEV_{max}$ and an increased $RFEV_{ROM}$ in the MRS condition. The increased $RFEV_{ROM}$ was a consequence of increased $RFIN_{init}$ and equal amounts of $RFEV_{max}$.

With respect to the global system, the rearfoot segment reached maximal eversion at a later point in time (t $RFGEV_{max}$) and revealed a greater $RFGIN_{ROM}$ for MRS compared to BF. Finally, $ASAG_{init}$ decreased by 9° for BF compared to MRS.

4. Discussion

One aim of the present study was to investigate lower leg kinematics in BF running and running in an MRS (Nike Free 3.0) to assess comparability of BF kinematics in both conditions. To systematically compare both conditions, we monitored influencing variables such as BF experience, preferred running strike pattern, speed, hardness and height of surface, and the athletes' level. Finally, we applied skin-mounted markers in both conditions to avoid bias due to marker placement. We hypothesized that running in an MRS does not alter lower leg kinematics compared to BF running. In summary, many differences in lower leg kinematics were found between the two conditions concerning transversal tibia, sagittal ankle and frontal rearfoot kinematics. Especially initial touch-down in frontal rearfoot and sagittal ankle kinematics were different between the two different conditions. Frontal rearfoot kinematics showed a more inverted rearfoot at touchdown and throughout the initial contact phase for MRS, whereas sagittal ankle kinematics showed a more dorsi flexed ankle joint and a higher sagittal touchdown angle in MRS. Additionally, timing of several maximal joint excursions for tibia and ankle in all planes were delayed in MRS compared to BF. Thus our hypothesis had to be rejected.

The results of our study have to be discussed mainly in two directions: first, a comparison with the existing literature and second, rating of findings with regard to proposed "barefoot features".

Differences in frontal rearfoot and sagittal ankle joint excursion at touchdown, or slightly prior to touchdown, have been reported in different studies.[4–7,13,19,20] Additionally Bonacci et al.,[4] Sinclair et al.,[6] and TenBroek et al.[13] found a less dorsi flexed ankle at touchdown for BF compared to the MRS condition and an even more increased dorsiflexion in TRS. Our data (absolute values) correspond very well with the data of Bonacci et al.,[4] and the absolute values of Sinclair et al.[6] and TenBroek et al.[13] differ slightly whereas the relative

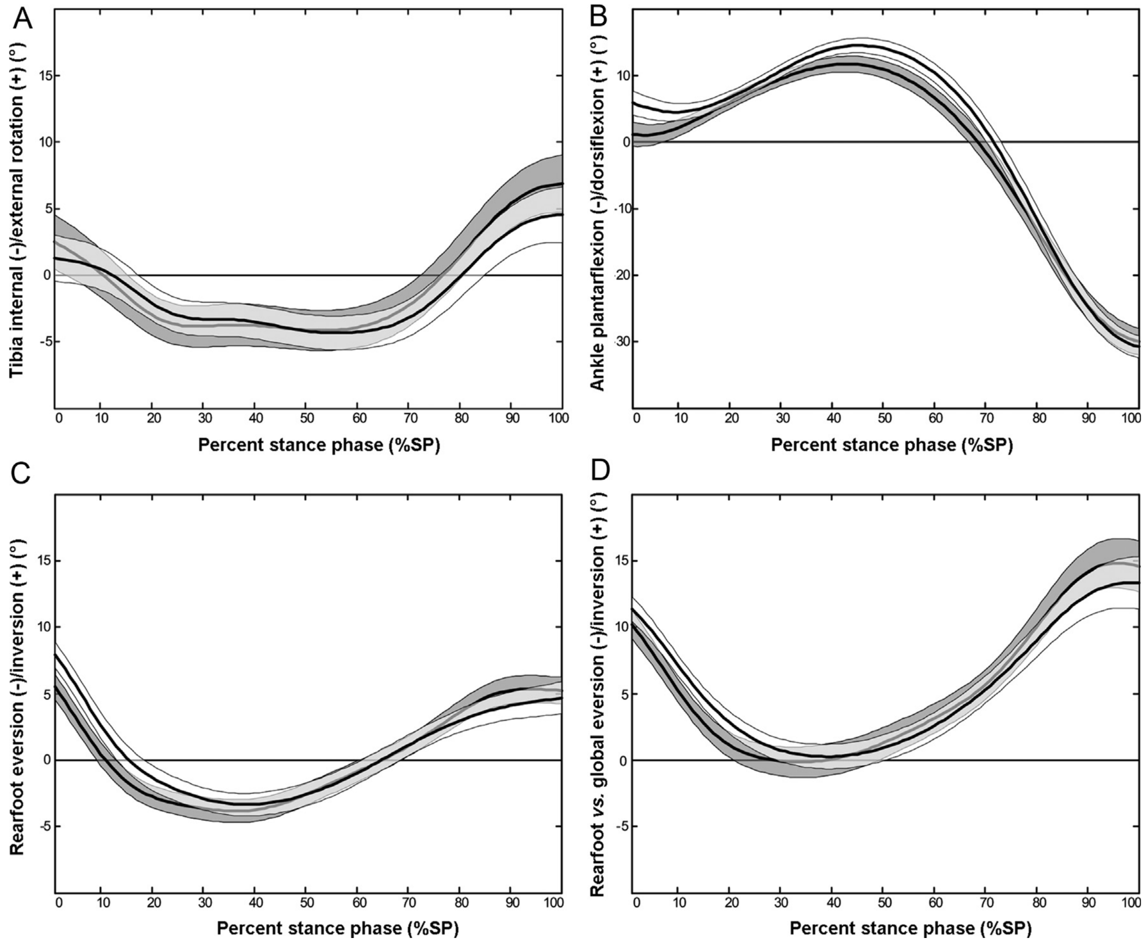

Fig. 2. Continuous joint excursion curves for barefoot running (BF, gray) and running with minimal running shoes (MRS, white): tibial external/internal rotation (A), ankle dorsi/plantarflexion (B), rearfoot inversion/eversion (C), and frontal rearfoot inversion/eversion with respect to the global system (D). Displayed are means and 95% confidence bands over the entire stance phase.

differences align well with our data. The studies by Bonacci et al.[4] and Sinclair et al.[6] used the same MRS that was used in our study. Different results were found in Squadrone and Gallozzi's article,[7] where no differences of sagittal ankle kinematics at touchdown were reported between BF and MRS, but between TRS and both other conditions. A reason for the contradictory result could be the slightly different method of data evaluation at touchdown phase. Thus, Squadrone and Gallozzi[7] analyzed sagittal ankle kinematics 15 ms prior to touchdown whereas the other studies including the current study analyzed joint excursion at touchdown. Further, the use of different MRS conditions (Nike Free 3.0 and Vibram FiveFingers™ (Vibram, Albizzate, Italy)) might also influence the results, since the Vibram FiveFingers™ is basically a sock that covers the foot. Lastly, although Paquette et al.[5] stated that there was no difference in strike patterns at touchdown for kinematics between BF and MRS with regard to TRS, the study results were not comparable with ours since Paquette et al.[5] evaluated pressure data instead of kinematic data. On the other hand, Bishop et al.[19] also reported a decrease in ankle joint dorsiflexion at touchdown for BF compared with TRS, whereas the absolute values corresponded well with the Sinclair et al. data.[6] Similar results were found in the study by De Wit et al.[20] in 2000. In summary, although influencing factors were not or hardly verified in many of the described studies and although the applied methods (2D *vs.* 3D) and calculation routines differ between the different approaches, we assume that our data support the current research even under a strictly monitored measurement setup. As we did not include a TRS condition in our study design, based on the findings from Sinclair et al.[6] and Squadrone and Gallozzi,[7] we would suppose sagittal ankle joint excursions wearing the Nike Free 3.0 to be between BF and TRS, whereas we presume the Vibram FiveFingers™ MRS to be closer to BF.

Our results present a more inverted rearfoot at touchdown and throughout initial contact phase for MRS, which seems to concur with the studies by Bonacci et al.[4] and TenBroek et al.[13] We assume an increased inversion of the rearfoot at touchdown to be a consequence of a more dorsiflexed ankle joint, since the tibialis anterior muscle, as main dorsiflexor muscle, also leads to increased inversion due to its insertion at the medial side of the foot. The study by Sinclair et al.[6] did not report any differences between BF and MRS, which is in contrast to our findings. We would presume that these contradicting results are due to the different marker sets at the foot and consequently due to the different calculation methods used to quantify frontal rearfoot motion. No differences between BF and MRS towards TRS were reported in either paper. No comparing data could be derived from Paquette et al.[5] or Squadrone and Gallozzi.[7] Further, no information about the inversion of the rearfoot at touchdown was found in the papers by Bishop et al.[19] and De Wit et al.[20] As we did not include a TRS condition in our study design, based on the above described findings we would assume that frontal ankle kinematics in wearing the Nike Free 3.0 might be closer to TRS than to BF (although the absolute differences between BF and MRS might be smaller).

No other studies were found that reported a delay in the timing of several maximal joint excursions in MRS compared to BF or compared with TRS for tibia, ankle, and rearfoot kinematics. From our point of view, these results might be explainable by the extreme flexibility of the midsole squares due to the numerous flex grooves in the Nike Free 3.0 in medio-lateral and anterior-posterior directions, whereas the foam runway, though comparable in hardness and height, showed consistent material properties with no flex grooves. Thus, this result might be setup-specific.

The differences in TER_{ROM} and $RFGIN_{ROM}$ between BF and MRS during the second half of the stance phase also seem to be setup-specific. We would speculate that the EVA foam cannot provide sufficient friction for a straight push-off phase. Thus, slight torsion under the forefoot may lead to an outward rotation of the rearfoot and finally to an increased inversion of the rearfoot during BF running. In contrast, the flexible rubber sole of the Nike Free 3.0 and the tartan surface produce enough friction to enable a straight push-off phase for MRS running.

Foot strike pattern at touchdown did not change in our study. This would indirectly support the findings of Gruber et al.[12] who reported different foot strike patterns when the same subjects were running on different hard surfaces. Thus, barefoot running does not change the landing automatically to forefoot running. Besides the hardness of the surface, other factors like speed and subjects' experience with BF running might attribute more to a change the landing pattern from rearfoot to forefoot or *vice versa*.

We are aware of several limitations to this study which must be considered. One major limitation is the missing TRS condition, meaning that kinematic data from BF, MRS, and TRS conditions could not be obtained and compared with recent literature. Since ground reaction forces were not measured and inverse dynamics not calculated, the authors cannot comment upon the occurrence of an impact peak at touchdown (to quantitatively determine strike pattern at touchdown), the differences in impact peaks, loading rates, or resulting joint moments between the two conditions. Quantifying and evaluating hip and knee kinematics would have been beneficial for the current study since the demonstrated differences in lower limb mechanics might alter hip and knee kinematics.[1]

5. Conclusion

The current study revealed differences between BF and MRS running in a controlled setup, especially during the initial stance phase of running for the sagittal ankle and frontal rearfoot motion. Proposed barefoot features could be partly demonstrated with the Nike Free 3.0. Nevertheless, changes in design of the Nike Free 3.0 should be considered in order to mimic BF movement even more closely. Foot strike at touch-down remained on the rearfoot, both in BF and MRS.

We believe a barefoot and individual running style and rearfoot strike pattern can be imitated by minimal running shoes. Further development of the Nike Free should focus on a rounded heel shape without any heel flare and a further reduction of the midsole height. Consequently, minimal running shoes might serve as a training device to strengthen small muscles around the ankle joint as shown by Brüggemann et al.[21] Future prospective studies are required to prove this beneficial aspect of minimal running shoes and to investigate whether injury rates can eventually be reduced as shown by Potthast et al.[22] Finally, studies addressing the relationship of BF running and performance would be beneficial to address the contradicting results of recent studies.

Conflict of interest

There are no conflicts of interest including financial, personal or other relationships with other people or organizations.

Acknowledgment

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