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Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners

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Aim. **The first aim of this study was to assess how changes in the mechanical characteristics of the foot/shoe-ground interface affect spatio-temporal variables, ground pressure distribution, sagittal plane kinematics, and running economy in 8 experienced barefoot runners. The second aim was to assess if a special lightweight shoe (Vibram Fivefingers) was effective in mimic the experience of barefoot running.**

Methods. **By using an instrumented treadmill, barefoot running, running with the Fivefingers, and running with standard running shoe were compared, analyzing a large numbers of consecutive steps. Foot/shoe-ground interface pressure distribution, lower limb kinematics, $\dot{V}O_2$ and heart rate data were simultaneously collected.**

Results. **Compared to the standard shod condition when running barefoot the athletes landed in more plantarflexion at the ankle. This caused reduced impact forces and changes in stride kinematics. In particular, significantly shorter stride length and contact times and higher stride frequency were observed ($P<0.05$). Compared to standard shod condition, $\dot{V}O_2$ and peak impact forces were significantly lower with Fivefingers ($P<0.05$) and much closer to barefoot running. Lower limb kinematics with Fivefingers was similar to barefoot running with a foot position which was significantly more plantarflexed than in control shoe ($P<0.05$).**

Conclusion. **The data of this study support the assumption that changes in the foot-ground interface led to changes in running pattern in a group of experienced barefoot runners. The Fivefingers model seems to be effective in imitating the barefoot conditions while providing a small amount of protection.**

KEY WORDS: Running - Exercise test - Shoes - Oxygen consumption.

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The activity of running has evolved from one that was critical to day-to-day survival to one that is considered important in overall fitness and longevity. As a consequence, millions of people are routinarily involved in running and jogging activities all over the world. Recently, following the footstep of self-pronounced “barefooters” like Ken Bob Saxton, who has been running marathons barefoot since 1997, a growing number of North Americans and Europeans recreational runners are discovering barefoot running.

Barefoot training has been used by coaches for a long time with the suggestion that this practice improves the strength of the overall muscle system and trains the intrinsic and extrinsic foot muscles.[1, 2] In addition, many published papers in medical journals support the claims that going barefoot is healthy and natural and that footwear is entirely unnecessary and, in many cases, detrimental to foot health.[2-7] Unfortunately, despite the skin of the foot is far more resistant than skin from other parts of the body, the available surfaces in developed countries are not always suited for this kind of training. Stones, pieces of glass, nails, and needles can cause wounds even when the plantar skin is thickened by adaptation to barefoot activity. Recently, to counter this problem and take advantage of the trend, Vibram (Vibram SpA, Albizzate, Italy) has proposed a very lightweight shoe called Fivefingers (Figure 1), which is supposed to mimic the barefoot

Figure 1.—The Vibram Fivefinger model.

experience while still providing a layer of protection. These footwear should provide just enough protection to the feet to run barefoot without worrying about puncture wounds, cuts and bruises.

Analysis of running has mostly been conducted by comparing different running techniques, running velocities, and shoe types. Until now, few authors have compared barefoot and shod running. With the exception of the study of Divert *et al.*[8] who used a multiple step protocol with the subjects running on an instrumented treadmill, in all previous studies the mechanical measurements involved repeated movement trials of a limited number of steps over one or two force platforms or pressure mats placed in the middle of a relatively short runway.[9-12] This methodology as a number of obvious limitations.[8, 13] Analysing a limited number of non consecutive steps limits the accuracy due to the inherent step variability. An additional source of variability was that the subjects must reach the force platforms with their normal running style without altering the running stride.[14] Having multiple force platforms did not solve this problem, as accurate placement for consecutive footstrikes is extremely difficult to achieve.

Another limitation of all those prior works was that the subjects used were not particularly experienced in barefoot running. Runners not accustomed to running barefoot could have their natural foot structure weakened by long-term footwear use and their proprioceptive sensitivity reduced.[2] So they could be less effective in adapting their running style when running in this condition. The subjects of our study trained regularly in barefoot conditions and participated in several competitive races barefooted. To our knowledge this is the first study which used subjects who regularly practice barefoot running.

The first aim of the current study is to extensively assess how changes in the mechanical characteristics of the foot/shoe-ground interface can affect spatio-temporal variables, ground pressure distribution, sagittal plane kinematics and running economy in experienced barefoot runners. The second aim was to assess if the Vibram Fivefingers were effective in replicate barefoot running conditions. Therefore, by using an instrumented treadmill, barefoot running, running with the Fivefingers shoe, and running with standard running shoe were compared, analysing a large numbers of consecutive steps.

Materials and methods

Subjects

Eight healthy male runners were the subjects of this study. They all had a long training experience in barefoot running and three of them had run even a marathon without shoes. They reported no injury at the time of experiment. They were informed about the procedures and signed a written consent. Their average characteristics were: age, 32±5 years; height, 1.75±0.05 m; body mass, 71±6 kg, 10-km race time, 40.3±4 min).

Protocol

Each subject came once to the laboratory for 2 test sessions. Although each runner was familiar with treadmill running, the primary purpose of the first test session was to get all the subjects used to the experimental condition. So each had adequate time to become accustomed to treadmill running prior to the introduction of the experimental load conditions. During the second session each subject was asked to perform 3 running bouts of 6 min at 12 km/h in a random order using his preferred foot striking technique. One of the bouts was carried out barefoot, another with the Vibram Fivefingers Classic (VF) model (average shoe mass: 148 g), and the latter in a neutral protective running shoe (retail price: 70-80 euros; average mass: 341 g). A rest period of 4 min separated the bouts. During the running trials, the foot shoe-ground interface pressure distribution, lower limb kinematics, $\dot{V}O_2$ and heart rate data were simultaneously collected.

Ten days before the test sessions each subject was given a pair of VF and a pair of the running shoes chosen as a control. This allowed them enough time to train with the new shoes and to get used to them.

According to Nyska *et al.*[15] walking and running patterns may be altered and unnatural when first performing in new shoes, so giving the subjects training and practice time with both the new shoes was to minimalise this problem.

Equipment and data collection

The Zebris FDM-T instrumented treadmill (Zebris Medical GmbH, Isny, Germany) was used to measure the foot or shoe-ground interface pressure distribution during the running bouts. The treadmill frame was made as rigid as possible and bolded firmly to the ground. This specific treadmill has the main advantage to allow fast recording and analysis of pressure data from a large number of steps at fixed velocity. The sensor element itself consists of high quality capacitive force sensors. In a treading area of 150×50 cm, the sensor unit comprises more than 5 378 force sensors. These sensors measure vertical force only. Because the size of the sensors is known (1.39 cm^2), the pressures can be determined automatically. Pressure data were sampled at 180 Hz during the last 20 s of each bout for a total of more than 60 consecutive steps analyzed and 5 378 (sensors) × 5 000 (samples) data points collected. The threshold level was set at 5 N/sensor to discard noise-related data. All above-threshold values were color-coded and were linearly distributed over 256 available colors between the threshold (blue) and the maximum value (red).

Stride length (defined as the distance covered with each stride), stride frequency, contact and flight times, and total vertical foot/ground force occurring during each stance phase were assessed by pressure data. Foot/ground force-time curves were inspected to determine peak impact forces and thrust peak forces. Using in-house software, regional analysis was performed to compute average peak pressure under the heel, midfoot, metatatarsal heads, toes, and hallux (Figure 2). The maximum pressure pictures for each step were analyzed to detect the single sensor exhibiting the highest pressure value in each of the above-mentioned footprint regions. In addition, the length of the line described by the center of pressure during the stance phase and the strike index were calculated. According to Cavanagh,[16] to calculate this last parameter a perpendicular line is drawn from the foot/shoe longitudinal midline to the initial center of pressure point. The distance along the midline from the heel to this perpendicular is then expressed as a percentage of total foot/shoe length. All the above described parameters were calculated from each step and averaged across trials for each participant and condition.

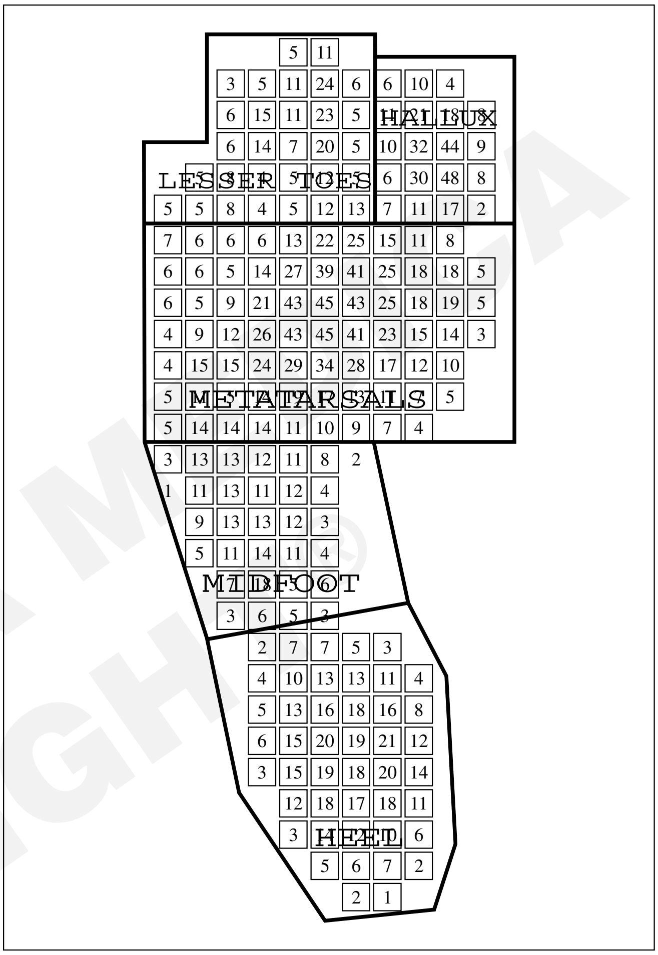

Figure 2.—Representation of the five plantar surface areas identified for regional analysis at the foot/ground interface.

To measure lower limb position, sagittal plane kinematic data were collected at 60 Hz with using a SVHS Sony videocamera during the last 20 s of each bout. Shutter speed was 1/1.500 s. The camera was mounted on a tripod placed 5 m from the treadmill and aligned so that the plane of the camera was parallel to the treadmill. The camera was leveled using the bubble level attached to the camera and set to the height of the subject's knee during quiet standing. A 0.5-m rod was held in the subject's plane of motion to provide a linear scale for subsequent digitizing.

To speed the digitizing process, circular markers

TABLE I.—*Spatio-temporal, kinetic, physiological and kinematic variables (means and standard deviations of 8 subjects).*

Variables	Barefoot (mean±SD)	Vibram fivefingers (mean±SD)	Running shoes (mean±SD)
Stride length (m)	2.19±0.2	2.29±0.16*	2.34±0.15*
Stride frequency (stride/min)	91.2±0.9	88.3±0.9*	86.0±1.1*
Step time (s)	0.327±0.002	0.343±0.002*	0.350±0.003*
Contact time (s)	0.245±0.002	0.242±0.002	0.255±0.002†
Flight time (s)	0.082±0.002	0.101±0.003*	0.096±0.003*
CP line length (mm)	133±6.4	150.3±3.8*	160.3±9*
Strike index (%)	58±6	56±5	40±6* †
Amplitude of the impact peak vertical force (BW)	1.62±0.4	1.59±0.5	1.72±0.4* †
Amplitude of the thrust peak vertical force (BW)	2.43±0.5	2.49±0.5	2.46±0.6
$\dot{V}O_2$ (mL kg^{-1} min^{-1})	45.7±2	45±2	46.3±2†
Heart rate (bps)	132±6	129±4	130±5
Knee angle -15 ms before touchdown (deg)	155±4	156±3	159±4
Ankle angle -15 ms before touchdown (deg)	94±5	93±4	87±5* †
Foot angle -15 ms before touchdown (deg)	3±4	4±4	12±4* †
Knee range of motion during the support phase (deg)	25±4	24±5	27±4
Ankle range of motion during the support phase (deg)	29±3	28±4	21±3* †

CP: center of pressure; BW: body weight. *Significantly different from barefoot condition; $P<0.05$. †Significantly different from vibram fivefingers; $P<0.05$.

were attached to the superior aspect of the acromion, greater trochanter, lateral condyle of the knee, head of the fibula, lateral malleolus, tuber calcaneum, and fifth metatarsophalangeal joint of the foot. For the shod conditions the last 2 markers were placed on the shoe in a matching position. The Dartfish Advanced Analysis Software (Dartfish Company, Fribourg, Switzerland) was used to digitize and analyse the videotape records. Kinematic data were processed to provide the foot angle relative to the ground, the knee and ankle joint angle just before the footstrike, and the peak knee flexion and ankle plantar-flexion angles that occurred after initial contact. The analysis allowed the ankle and knee range of motion during stance phase to be determined. A neutral ankle was expressed as 90 degrees. Dorsiflexion was indicated by a decrease in this value and plantar flexion as an increase.

During the treadmill runs, $\dot{V}O_2$ and heart rate were monitored every 15 s employing a K4B^2 portable metabolic system (Cosmed srl, Rome, Italy) whose $\dot{V}O_2$ measurement accuracy and reliability have been assessed in earlier studies.[17, 18] Steady-state oxygen consumption rates associated with the different running conditions was measured by averaging the $\dot{V}O_2$ measurements over the last two minutes of each running bouts.

Statistical analysis

Each runner's mean value of the variables described above was calculated for each foot condition. Group mean values were then computed. A Kolmogorov-Smirnov normality test proved all variable to be normally distributed. Consequently, repeated measures ANOVA, followed by a *post hoc* Tukey test were used for statistical evaluation. Significance was accepted at $P<0.05$ level.

Results

Stride length and stride frequency was significantly ($P<0.05$) lower and higher when running barefoot (Table I). As a consequence, step time was significantly lower when running barefoot ($P<0.05$). Contact time was significantly different ($P<0.05$) comparing VF and standard shod running, while flight time was significantly lower in barefoot running. The length of the center of pressure line was significantly lower ($P<0.05$) when running barefoot compared with the other two conditions. Strike index was significantly lower in standard running shoe ($P<0.05$).

Kinetic and pressure distribution parameters

Magnitude of impact peak forces were significantly higher ($P<0.05$) when running in the standard running shoes. Across the three conditions, no significant differences were found in the thrust peak forces, although there was a trend of higher values when running with VF compared to barefoot. Figure 3 shows typical curves of vertical forces for one subject. To note the different shape of the curves in the early stance phase.

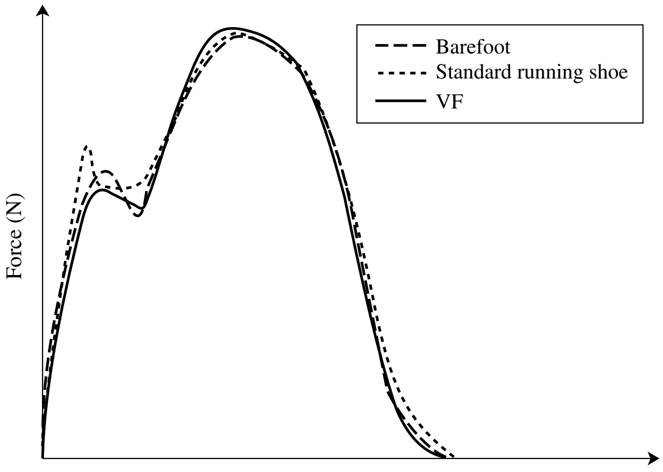

Figure 3.—Total vertical foot/ground force amplitude variations over time for one representative subject in the three experimental conditions. VF = Vibram Fivefingers model.

Considering all the subjects, the peak local pressure under the heel, midfoot and hallux, was significantly higher ($P<0.05$) when running in standard running shoe compared to the other two conditions (Figure 4). Peak pressure under the toes was significantly higher ($P<0.05$) with VF compared to barefoot running.

Physiological variables

$\dot{V}O_2$ values was significantly lower ($P<0.05$) when running with VF compared to running in standard shoe. No significant difference was found between barefoot and both shod conditions. Across the three conditions, no significant differences were found in the heart rate values.

Kinematic variables

Examining joint angles just before touchdown, significant differences were found at the ankle joint with the subjects landing significantly more dorsiflexed ($P<0.05$) with the standard running shoes compared to the other two conditions (Table I). No significant differences were observed at the knee joint. Similarly, significant differences were found in the total range of motion at the ankle joint with significant more joint excursion ($P<0.05$) when running with the VF compared to standard running shoes, while no significant differences were observed at the knee joint.

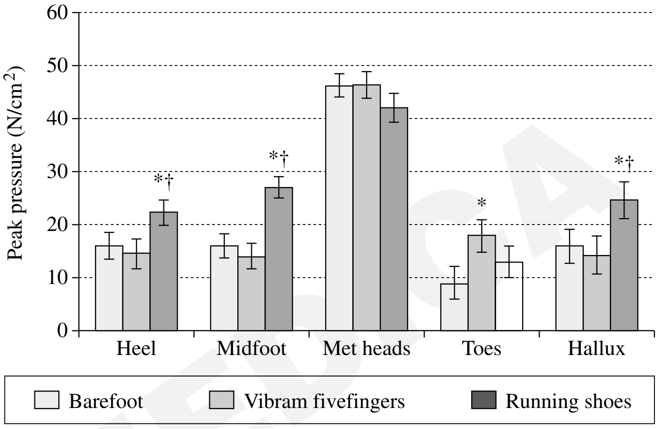

Figure 4.—Peak pressure values measured in selected sites of the foot/shoe-ground interface.

Discussion

Using a group of runners used to train barefoot, the differences in spatio-temporal variables, ground pressure distribution, sagittal plane kinematics and running economy among three different running conditions were analyzed in order to gain more insight in the adaptation of the athletes in changes in the mechanical characteristics of the foot-ground interface. In particular, we will discuss: 1) the differences between barefoot and standard running shoe; 2) the differences between barefoot and VF model to verify if this special shoes is effective in mimic the barefoot condition.

Barefoot versus *running in standard running shoes*

In this study, contact time was significantly lower (245 *versus* 255 ms) while stride frequency was significantly higher in barefoot condition (91.2 *versus* 86.0 stride/min). Stride length was higher in the shod condition (2.34 *versus* 2.19 cm). These results agree with those previously found by De Witt *et al.*[9] in 9 long distance runners and Divert *et al.*[8] in 31 subjects who run on an instrumented treadmill at the same speed. In these studies, it was hypothesized that these adjustments in stride kinematics could help to limit the larger impact forces experienced in running barefoot and that should be absorbed by the muscular-skeletal system at each step. The significant lower values of peak vertical force at the impact observed in our subjects when running barefoot (1.62 *versus* 1.72

BW) further support this hypothesis. Similar results were found by Divert *et al.*,[8] even if they measured higher amplitude differences between barefoot and shod condition. In contrast, no significant difference was observed by De Wit *et al.*[9] for running speeds between 3.5 and 5.5 m/s and by Dickinson *et al.*[19] in 6 subjects running across a force plate. In both those works impact peak force amplitudes were considerable higher than those recorded in our study. Many methodological differences may explain the divergent results. Firstly, the subjects of the previous works were all rearfoot strikers and likely not accustomed to running barefoot. This could have reduced their ability to dampen the forces elicited at the impact while barefoot. According to Robbins *et al.*[7, 20] adaptation to barefoot running could take several weeks. Furthermore, the subjects run in a lab runway and a limited number of steps were analyzed. As suggested by Divert *et al.*,[8] it is possible that, when data are collected on limited number of steps, runners are able to sustain and then to maintain high impact forces. Differently, longer running trials, as those experienced by our subjects would lead the athletes to adopt strategies to reduce the stress under the heel. Additionally, step variability could have limited the accuracy of the previously reported results. Indeed, the majority of prior studies on mechanical data collection during human locomotion did evidence the extremely large intrasubject variability of step parameters with the obvious need to adopt multiple trial protocols to achieve statistical significance.[14, 21-24]

The subjects of our study seem to realize the changes in stride kinematics varying the lower limb touchdown geometry. In particular, kinematic data showed that when running barefoot the athletes adopted a flatter foot placement at the footstrike compared to running in standard shoe, indicating a full forefoot strike. As a consequence, barefoot peak pressure values were reduced under the heel (16 *versus* 22 N/cm^2) and higher underneath the metatarsal heads (48 *versus* 42 N/cm^2). This agrees with De Witt *et al.*[9] who speculated that the runners adopted a flatter foot placement when running barefoot in an attempt to reduce local pressure under the heel. Robbins and Gouw [25] argued that plantar sensation induces a plantar surface protective response whereby runners alter their behavior to reduce shock. According to them, cushioned shoes would provoke a sharp reduction in shock-moderating behavior, thus increasing impact forces. If we consider barefoot running as an extreme hard shoe-condition,[9] the above consideration also agrees with the findings of Hennig *et al.*,[26] who concluded that runners tend to alter their landing pattern to elicit lower impact forces when running in shoes with harder soles.

In this study, running barefoot decreased the energy cost of running by 1.3% in $\dot{V}O_2$. The observed differences were no statistical significant and lower than those previously found in other studies. Flaherty,[27] for example, found that oxygen consumption during running at 12 km/h was 4.7% higher in shoes of 700 g-mass per pair than in bare feet. The lack of significant differences in $\dot{V}O_2$ between barefoot and shod condition observed in the present study could have several methodological causes. Our subjects were used to train barefoot, this could have changed their running style making their running more economical even when performing in cushioned shoes. The relatively high strike index (40%) measured when running in the standard running shoe is higher than those typically reported for rearfoot strikers [28] and indicates that landing occurred more toward the midfoot. In addition, the fact that our subjects landed with the foot more plantarflexed in both barefoot and shod condition compared with the subjects of other studies [8] support the hypothesis that they could have modified their running behavior. Another possible explanation for the absence of significant differences in running economy could be found in the relatively low speed at which our athletes performed considering their fitness level. At this low speeds the principle of minimizing the loss of energy that was successful for power activities such as sprinting, running at higher speeds, and jumping may not be valid.[29] Additional studies should be carried out with the same athletes running at higher velocities.

Barefoot versus *Fivefingers shoes*

The values of the spatio-temporal variables observed with VF seem to be closer to those obtained with the standard running shoe compared to barefoot running, with the exception of contact time which was significantly lower when running with VF compared to standard shod condition (0.242 *versus* 0.255 s). In particular, step time and stride frequency were respectively higher (0.343 *versus* 0.327 s) and lower (88.3 *versus* 91.2 stride/min) with the VF model than barefoot. The difference in stride time was mainly due to a difference in the airborne phase duration, being contact time very close (0.242 *versus* 0.245 s). In contrast, the peak vertical force at the impact was significantly lower in VF compared to standard shod condition (1.59 *versus* 1.72 BW) and much closer to barefoot running (1.59 *versus* 1.62 BW). The lower limb kinematics with VF was similar to barefoot running, with the foot landing more towards the forefoot with a foot position which was more plantarflexed than in control shoe. The fact that the lower extremity kinematics did not change with the exception of the plantar-dorsiflexion angle is in agreement with the concept that in normal situations, the joint movements are primarily determined by the "preferred movement path" in each joint.[30]

Even if the difference was not significant, likely due to the small sample size, the thrust peak vertical forces were higher with VF compared to barefoot indicating that the VF allowed the runners to push more vigorously than barefoot. This could explain the longer stride length obtained in this condition compared to barefoot. Likely the thin rubber sole of the VF is enough to permit plantar discomfort to be sensed and moderated, a phenomenon that Robbins and Gouw [25] termed "shock setting".

Running with VF required a significant 2.8% decrease in oxygen consumption compared to the standard running shoe. The most important differences between VF and the control shoe were their mass, and the thickness and stiffness of their sole. The mass difference for a pair was 400 g. It was found [31] that a difference of 100 g corresponds to between 0.5% and 1% in $\dot{V}O_2$. Thus, the differences may be caused primarily by the mass difference. This is in line to what was found in literature.[27] Another possibility is that the work done in compressing and flexing the sole and in rotating the sole during the ground-up was less with VF compared to the standard running shoe. Frederick [32] reported that $\dot{V}O_2$ increased substantially with thicker shoes inserts during treadmill running.

While the differences in $\dot{V}O_2$ between VF and the control shoe were expected and supported by what was found in literature, less expected was the finding that running with VF required less energy than running barefoot. In this case the total difference in weight was about 300 g. The reason of the latter finding may only be speculated from the data of this study. Previous works showed an increase in energy cost of running when performing on stiffer surfaces compared to less stiff ones, and hypothesized that for each subject exists an optimal stiffness to improve running economy.[33] Considering barefoot running as one extreme hard shoe condition or as running on a stiff surface,[9] it could be speculated that for our subjects the stiffness level obtained when wearing the VF made their running more economical compared to the other two conditions.

The sample size of this experiment (8 participants) was too small to allow definite conclusions to be drawn and to allow further statistical analysis. The investigation should be extended to see if the trends evidenced can be projected. Sample size was mainly limited due to our choice to utilize as subjects athletes who were used to running barefoot. An additional cause was the need for VF shoes and standard running shoes to be supplied in the correct sizes to all the subjects at least 10 days before the test sessions.

Another limitation of the present work could be find in the simplified 2-D model we used to analyze the lower limb kinematics. Modification in frontal and transverse plane at the ankle, knee, and hip under the different foot-ground interface could not be examined. In addition, lower limb motion was filmed at 60 frames per second with a shutter speed of 1/1.500 s. Although higher frame rates are usually encountered in the literature on running, 60 Hz yielded satisfactory results when recording lower limb kinematics of subjects running at this relatively low speed. This was well documented by Van Gheluwe *et al.*[34] However, it is reasonable to expect that the 60 Hz frame rate may have limited the absolute accuracy of the calculated angular values measured at the footstrike.

Conclusions

The data of this study support the assumption that changes in the foot-ground interface led to changes in selected running related variables in a group of experienced barefoot runners. Compared to the standard shod condition, when running barefoot the athletes landed in more plantarflexion at the ankle reducing impact forces under the heel. This caused changes in stride kinematics. In particular, shorter stride length and contact times and higher stride frequency were observed. The VF model seems to be effective in imitating the barefoot conditions while providing a small amount of protection. This allows the runners to push more vigorously as evidenced by the higher pressure under the metatarsal head, the higher step length, the lower step rate, and the higher thrust peak force compared to barefoot condition. Oxygen consumption was lower than that measured when running barefoot even if the reason of this finding can only be speculated from our data.

Future researches should include a large number of subjects running at higher speeds and a 3-D kinematic analysis to investigate changes that occurs in the frontal and transverse planes at the foot ankle complex, knee and hip. In addition, since our subjects run on treadmill, further studies are needed to establish how this special shoe affect impact force and shock-moderating behavior on natural surfaces.

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