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Patellofemoral Joint Loads during Running Immediately Changed by Shoes with Different Minimalist Indices: A Cross-sectional Study

Chenhao Yang [1], Songlin Xiao [1], Yang Yang [1], Xini Zhang [1], Junqing Wang [1] and Weijie Fu [1,2,*]

[1] School of Kinesiology, Shanghai University of Sport, Shanghai 200438, China; chyang9610@163.com (C.Y.); xiao_songlin@126.com (S.X.); 18049922807@163.com (Y.Y.); zhangxini1129@163.com (X.Z.); wangjunqingray@163.com (J.W.)

[2] Key Laboratory of Exercise and Health Sciences of Ministry of Education, Shanghai University of Sport, Shanghai 200438, China

* Correspondence: fuweijie@sus.edu.cn or fuweijie315@163.com; Tel.: +86-21-65507368

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Abstract: Purpose: Given the high incidence of patellofemoral pain syndrome (PFPS) in runners, this study aimed to investigate the immediate effect of shoes with different minimalist indices (MI) on the mechanical loads of the patellofemoral joint. Methods: Fifteen healthy male rearfoot strike runners were recruited to complete overground running trials at 3.33 m/s (±5%) in two running shoe conditions (MI = 26% versus MI = 86%). The amount of ten Vicon infrared cameras (100 Hz) and two Kistler force plates (1000 Hz) were used to collect kinematic and ground reaction force (GRF) data simultaneously. Quadriceps strength, patellofemoral contact force, patellofemoral contact area, and patellofemoral contact stress were calculated. Results: No significant differences were observed in the impact force and the second peak of the vertical GRF between the two shoe conditions. Compared to wearing low-MI shoes, wearing high-MI shoes showed that the maximum flexion angle of the knee, the contact area of patellofemoral joint and the peak knee extension moment reduced significantly ($p < 0.01$), and the peak patellofemoral contact force and stress decreased significantly ($p < 0.05$). Conclusion: These findings suggest that wearing high-MI shoes significantly decreases the patellofemoral contact force and patellofemoral joint stress by reducing the moment of knee extension, thus effectively reducing the load of the patellofemoral joint during the stance phase of running and potentially lowering the risk of PFPS.

Keywords: minimalist index; patellofemoral contact force; patellofemoral contact stress; footwear; patellofemoral joint pain syndrome

1. Introduction

Hundreds of millions of citizens participate in sports, among which running is widely known. Injury remains high with the popularity of running, with 19.4% to 79.3% sustaining a running-related injury annually [1]; patellofemoral pain syndrome (PFPS) is one of the most common running injuries, exhibiting the highest incidence of 17% in the specific pathologies of running-related injuries [2]. Increased patellofemoral joint stress (PFJS) was determined as an important pathogenic factor [3]. The knee joint features a complex structure; the soft tissue and muscles maintain the stability of the tibia [4]. Thus, any change in mechanics may influence the force distribution around the patellofemoral joint. Studies have shown that patients with patellofemoral joint pain exhibit different biomechanical characteristics during running [5]. Therefore, changes in knee joint torque, patellofemoral contact force and stress during this activity may affect the risk of PFPS. Correspondingly, the mechanism of overwork injury is due to the cumulative effect of repeated high-load work of the muscles and bones [6];

therefore, reducing the knee load to a certain extent may considerably decrease the cumulative effect of long-term running on the knee joint.

With the development of technology, new materials and designs have been applied to sports shoes, especially midsole structures, to reduce the load on the lower extremities. The unique mechanical structures of different sports shoes can change the force characteristics of the human running gait [7]. For healthy runners, wearing different sneakers can affect the biomechanical characteristics of the lower extremities, such as stride frequency, ground contact angle, vertical load rate and joint force [8]. In recent years, barefoot running has become increasingly popular, and many runners have been opting for minimalist shoes, which provide basic protection but limited cushioning. The standardised definition of minimalist shoes, the Minimalist Index (MI), was developed to allow running shoes to be distinguished based on their degree of minimalism, and may help to decrease injuries related to footwear transition [9]. Numerous studies have verified [7,10,11] that minimalist shoes can change the landing posture of the lower limbs, mainly focusing on the adaptation of the ankle joints, that is changing the angle between the foot and the ground, the tendency of forefoot pattern strike and the adaptability of the calf triceps and the Achilles tendon. Relatively few studies have focused on knee load and this condition limits the understanding of the relationship between sneakers and knee joints, especially the patellofemoral joint.

This study aimed to determine the biomechanical characteristics of the patellofemoral joint during running. To achieve this the immediate effects of wearing running shoes with different minimalist indices on patellofemoral contact force (PFCF) and patellofemoral contact stress (PFJS) were explored. Based on the previous observations, it was hypothesized that PFCF and PFJS would decrease when wearing running shoes with high Minimalist Index (MI), e.g., minimalist shoes.

2. Materials and Methods

2.1. Participants

A total of fifteen recreational and healthy male runners (age: 31.4 ± 6.6 years; height: 174.7 ± 6.3 cm; body mass: 73.2 ± 9.8 kg; weekly running volume: 30.6 ± 9.5 km) were recruited. Inclusion criteria were as follows: 1) The weekly running volume in the past month was over 20 km; 2) rearfoot strikers and to be accustomed to wearing cushioned shoes; 3) no experience in barefoot running nor wearing minimalist shoes or special sneakers (e.g., five-finger shoes and racing spikes); 4) suffered no musculoskeletal injuries within three months prior to the tests. A two-tailed t-test was executed via the G*Power 3.1 software (Univ. Kiel, Kiel, Germany) to determine whether a sample size of 15 was sufficient to minimize the probability of type II error for all the variables ($P = 80\%$ at $\alpha = 0.05$).

This study, with detailed guidelines for participants' safety and experimental protocols, was approved by the Institutional Review Board of the Shanghai University of Sport (No. 2017007). The study was conducted in accordance with the declaration of Helsinki. Specifically, all procedures and potential hazards were clarified to the participants in nontechnical terms, and informed consent was signed prior to the tests. All participants had full knowledge of test procedures and requirements.

2.2. Shoe Conditions

A rating scale for the running shoes was developed in accordance with the work of Esculier et al. [9] and the MI was defined as the minimalism of different running shoes. Specifically, the MI of running shoes was calculated according to guidelines by weight, heel-to-toe drop, stack height, motion control/stability technologies and flexibility. The motion control/stability technologies included multi-density midsole, rigid heel counter, elevated medial insole under the foot arch, and tensioned medial upper. Flexibility included longitudinal and torsional flexibility. A high MI indicated high minimalism of running shoes.

In this experiment, the size of the experimental shoes ranged from EUR 41 to 43 based on the foot size of the participants. The used minimalist shoes were the INOV-8 Bare-XF 210 V2 series

(Figure 1). The outsole of the shoe was made of INOV Corp.'s patented viscous rubber, which measured approximately 3 mm in thickness, and the shoes contained no cushioning midsole. The upper was made of a mesh composite material, which was light, breathable, fitted the foot surface and was good for toe movement during running. The heel-to-toe drop of the shoe was 0 mm, the weight (EUR size 42) was 227 g, and the MI = 86%. The used cushioned shoes were the Nike Air Zoom Pegasus 34. EVA foam was used in the midsole of this brand, and a Zoom Air cushion was set in the heel and the forefoot. The heel-to-toe drop was 7 mm, the weight (EUR size 42) was 285 g, and the MI = 26%. The runners were required to wear uniform Nike Dri-FIT socks to eliminate interference. Table 1 shows the specific MI of the two experimental shoes.

Figure 1. Shoes used in the experiment. Minimalist shoe: INOV-8 Bare-XF 210 V2 (**left**). Cushioned shoe: Nike Air Zoom Pegasus 34 (**right**).

Table 1. Detailed comparison of the Minimalist Index (MI) of the two shoes.

Shoe	Weight (g)	Stack Height (mm)	Heel-to-Toe Drop (mm)	Stability and Motion Control Technologies	Flexibility	MI (%)
INOV-8 Bare-XF 210 V2	227	3	0	None	longitudinal 360° torsional 360°	86
Subscore	2	5	5	5	4.5	
Nike Air Zoom Pegasus 34	285	30	7	Four devices	longitudinal 45°–90° torsional 0°–45°	26
Subscore	1	1	2	1	1.5	

Notes: Four stability and motion control technologies of the Nike Air Zoom Pegasus 34: multi-density midsole, rigid heel counter, supportive tensioned medial upper and medial flare. MI = sum of subscore × 4 × 100%.

2.3. Data Collection

First, the experimental process was explained to the participants and they signed the relevant questionnaire and informed consent. The same uniform sportswear was replaced, and forty infrared retroreflective markers (diameter: 14.0 mm) were attached bilaterally to both of the lower extremities to define hip, knee, and ankle joints according to the plug-in gait marker set [12]. Before the experiment, the participants performed a 5-min warm-up on a treadmill at an optional running speed only with cushioned shoes, followed by a 1-minute 3.33 m/s experimental speed adaptation. Meanwhile, it was the first time that they had worn minimalist shoes, which was considered as "immediately". After completing the preparation, the participants began the formal experimental tests.

Two 90 × 60 × 10 cm Kistler 3D force platforms (9287B, Kistler Corporation, Switzerland) were used to collect ground reaction force (GRF) data at a sampling rate of 1000 Hz. A 10-camera infrared 3D motion capture system (Vicon T40, Oxford Metrics, UK) was used to collect the trajectory markers (14.0 mm in diameter) of the bone landmarks of the lower extremities to define the knee joint at a sampling rate of 100 Hz (Figure 2). The participants randomly wore one of the shoes. A 5–10 minute break was provided between two shoe tests to eliminate the potential interference. Three running trials were collected per condition at 3.33 m/s (±5%). This target speed was common for recreational runners and all participants completed running trials without any discomfort. Running speed was monitored by the use of a Witty-Manual grating timing system (Micro gate, Italy) positioned 4 m apart along a 20 m runway. Meanwhile, the participants were required to run back and forth until three successful steps (trials) in which the foot of the dominant lower extremity (defined as preferred kicking leg [13]) was completely on the force plate were collected for each shoe condition. Each trial that met the following criteria was deemed successful: 1) The speed was 3.33 m/s (±5%) within the capture volume; 2) no relative sliding occurred between the shoes and the force plate.

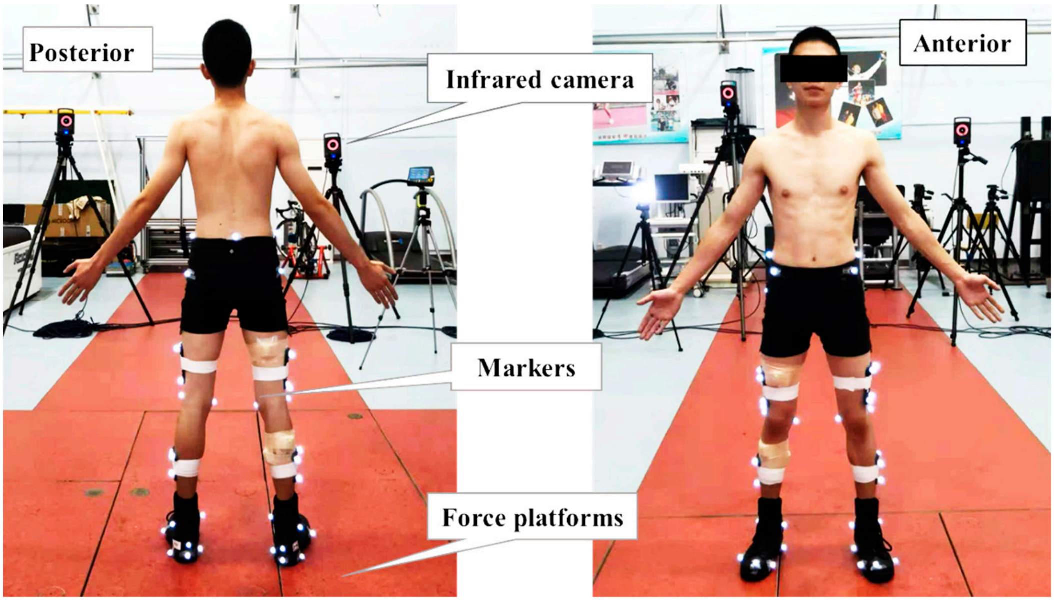

Figure 2. Set of reflective markers used in the study and the experimental setup.

2.4. Data Processing

Knee load during running was generally assessed by the peak torque of knee extension, patellofemoral contact force (PFCF) and patellofemoral contact stress (PFJS) [14,15]. First, marker trajectories were filtered with a cut-off frequency of 7 Hz via the gait analysis software Visual 3D (v5, C-Motion, Inc., Germantown, MD, USA). We established a 3D model in Visual 3D to calculate the GRF, knee flexion angle, torque of knee extension, angle of the knee joint when the runners touch the ground, angle of the ankle joint and the angle between the foot and the ground (foot inclination angle). The relevant parameters of the stance phase were standardised in time (0–100%), and a curve was plotted using the averages to identify the differences between the biomechanical parameters of the knee and various MI running shoes in the entire stand phase. In addition, PFCF, PFJS and related parameters were calculated by referring to previous studies. The details of the cited model were as follows.

The contact area (mm^2) between the patella and femur was a function of the sagittal knee angle and expressed as follows [16]:

$$S_{PFCA} = 0.0781 \times {\theta_i}^2 + 0.06763 \times \theta_i + 151.75 \tag{1}$$

where S_{PFCA} represents the contact area between the patella and the femur, and θ_i (°) was the sagittal angle of knee extension and flexion (Figure 3).

The effective arm of the quadriceps force (L_A, m) was a function of the sagittal knee angle and expressed as follows [17]:

$$L_A = \begin{cases} 0.036\theta_i + 3.0\ (0 \le \theta_i < 30^\circ) \\ -0.043\theta_i + 5.4\ (30 \le \theta_i < 60^\circ) \\ -0.027\theta_i + 4.3\ (60 \le \theta_i < 90^\circ) \\ 2.0\ (90 \le \theta_i < 120^\circ) \end{cases} . \tag{2}$$

Quadriceps force (N) was calculated as follows [14]:

$$F_Q\ (\theta_i)\ =\ M_{EXT}(\theta_i)/L_A\ (\theta_i) \quad (3)$$

where F_Q is the quadriceps force, and M_{EXT} is the extension moment (N·m).

The patellofemoral contact force (F_{PF}, N) was calculated as follows [17]:

$$F_{PF} =\ 2F_Q \sin(\beta/2) \quad (4)$$

where $\beta\ = 30.46 + 0.53(\theta_i)$, F_{PF} (N) is PFCF, and β (°) is the angle of the quadriceps line and patellar ligament (Figure 3).

The patellofemoral contact stress (MPa) was calculated as follows:

$$P_{PFS} =\ F_{PF}\ /S_{PFCA}\ (\theta_i) \quad (4)$$

where P_{PFS} is the PFJS.

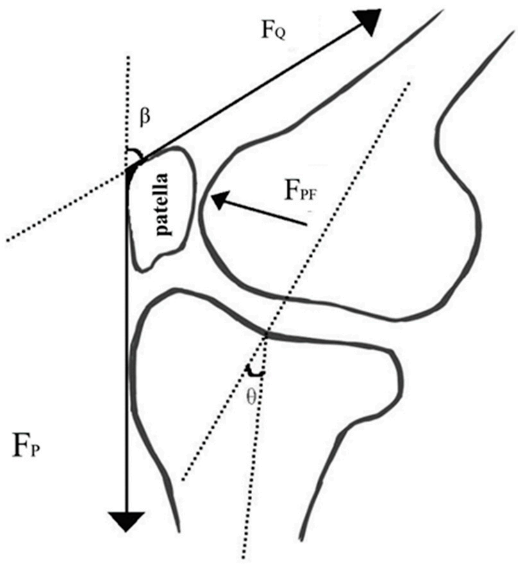

Figure 3. Free-body diagram of the patellofemoral joint. Notes: F_Q refers to the quadriceps muscle strength, F_{PF} denotes the patellofemoral contact force, F_P represents the patellar ligament tension line, β stands for the angle between the quadriceps muscle line and the patellar ligament tension line, and θ is the knee flexion angle.

2.5. Statistics

All the dependent variables were normally distributed, as indicated by the Shapiro–Wilk test. The paired *t*-test was used to determine the differences in all variables (GRF and joint mechanics) between the MI 86% and MI 26% of shoes (25.0, SPSS Inc., Chicago, IL, USA). The significance level was set as $\alpha = 0.05$.

3. Results

3.1. GRF

The vertical GRF (vGRF) of all the runners using both shoes exhibited two peaks. For the Minimal Index (MI) 86% and MI 26% shoes, no significant differences were observed between the impact force (first peak, FP) and the peak vGRF (second peak, SP) during the stance phase ($p > 0.05$) (Table 2).

3.2. Kinematics

The foot inclination angle at foot strike was positive regardless of shoe conditions, indicating that all the runners ran with a rearfoot strike. No statistical differences were identified between the knee flexion angle and the ankle plantar flexion angle at the moment of foot strike ($p > 0.05$). However, with the MI 86% shoes, the foot inclination angle significantly reduced by 35.6% ($p < 0.05$). Moreover, the peak knee flexion angle and the peak contact area of the patellofemoral joint were significantly lower than those with the MI 26% shoes, in which the peak knee flexion angle decreased by 6.5% and the peak contact area of the patellofemoral joint reduced by 5.4% ($p < 0.05$) (Table 2). The curve of the entire stance phase with the minimalist shoes indicated a considerably lower knee flexion angle than that with the cushioned shoes in the middle and late phases (Figure 4A).

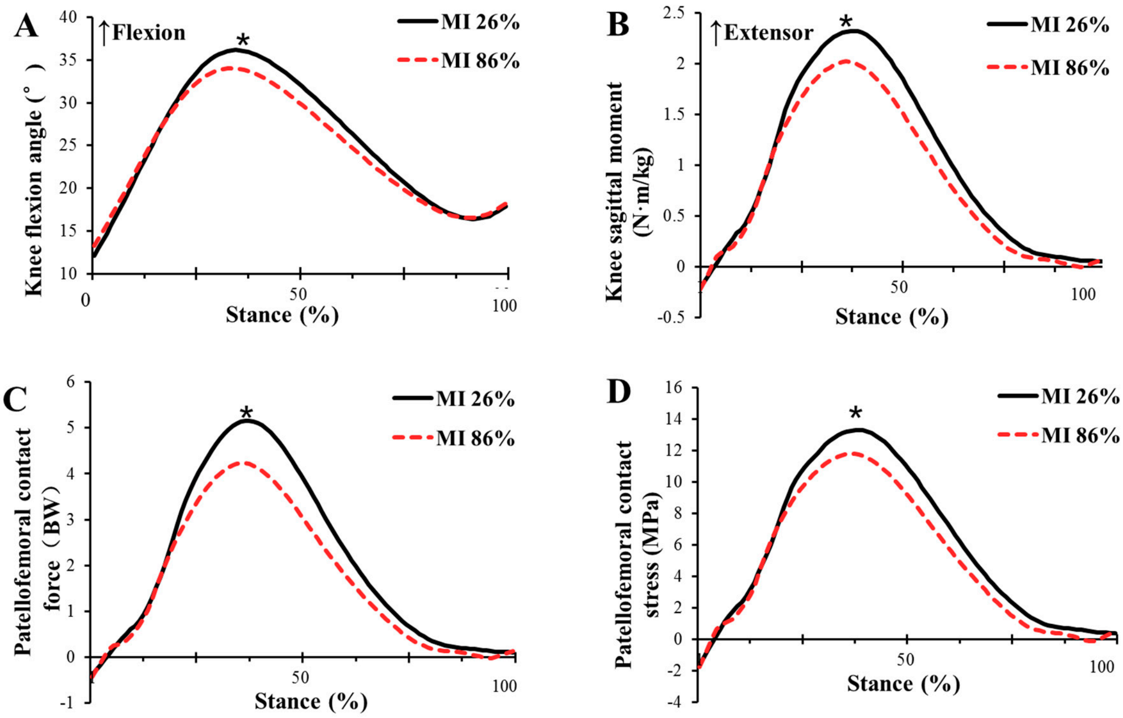

Figure 4. Comparison of the mean values of knee kinematics and kinetics from all participants between shoe conditions (MI 26%: cushioned shoes; MI 86%: minimalist shoes). (**A**) knee flexion angle during stance phase; (**B**) knee sagittal moment during stance phase; (**C**) patellofemoral contact force during stance phase; (**D**) patellofemoral contact stress during stance phase. *$P < 0.05$.

3.3. Kinetics

At the peak knee extension moment, the peaks of PFCF and PFJS were significantly lower with the MI 86% shoes than with the MI 26% shoes, in which, at the peak knee extension moment, the peaks of PFCF and PFJS reduced by 12.3%, 17.0% and 10.4%, respectively ($p < 0.05$) (Table 2). Consistent with the knee flexion angle curve, the curves of the abovementioned knee loading parameters were lower under the MI 86% shoe condition during the middle- and late-stance phases than those under the MI 26% shoe condition (Figure 4B–D).

Table 2. Sagittal plane kinematics and kinetics during running with two different shoe conditions ($\overline{x}$ ± SD.

Phase	Parameters	MI 26%	MI 86%	p
Touch-down	Knee flexion angle (°)	12.64 ± 4.56	13.56 ± 5.60	0.637
	Ankle plantar flexion angle (°)	0.13 ± 7.92	0.13 ± 4.29	0.835
	Foot inclination angle (°)	12.54 ± 2.18	8.07 ± 4.64	<0.001
Stance phase	FP (BW)	1.74 ± 0.23	1.78 ± 0.16	0.701
	SP (BW)	2.59 ± 0.31	2.61 ± 0.25	0.559
	Peak knee flexion angle (°)	36.29 ± 3.41	33.93 ± 1.74	0.008
	Peak patellofemoral joint contact area (mm^2)	280.10 ± 21.96	265.08 ± 10.20	0.008
	Peak knee extension moment (N × m/kg)	2.36 ± 0.41	2.07 ± 0.47	<0.001
	Peak patellofemoral contact force (BW)	5.23 ± 1.12	4.34 ± 0.97	<0.001
	Peak patellofemoral contact stress (MPa)	13.48 ± 2.64	12.08 ± 3.27	0.015

Notes: Foot inclination angle is the angle between the foot and the ground. The FP (the first peak of the vGRF) and SP (the second peak of the vGRF), knee extension moment and patellofemoral contact force are standardised by body weight (BW). MI 86%: minimalist shoes. MI 26%: cushioned shoes.

4. Discussion

This study aimed to determine the immediate effects of wearing shoes with different Minimal Index (MI) on the patellofemoral joints and to explore whether directly changing shoes can reduce knee load and the risk of patellofemoral pain syndrome (PFPS). The conventional belief is that the cushioned structure of running shoes can reduce the impact force during running and protect the lower limbs. In this study, however, the MI 26% shoes caused no change in the impact force during the stance phase and the ankle/knee flexion angle at touchdown compared with those with the MI 86% shoes. Moreover, during the transition and propulsive phases of the stance phase (20–100%), wearing the MI 86% shoes can effectively reduce the patellofemoral contact force (PFCF) and patellofemoral contact stress (PFJS) by changing the parameters of knee loads, such as the knee flexion angle and knee extension moment. The mechanism of PFPS is that the patellofemoral joints are subjected to excessively high loads [14,18,19]. Therefore, the results of this study suggest that running in high-MI running shoes might be beneficial for reducing the risk of PFPS.

This finding is consistent with those in previous studies [20,21]. Sinclair and Esculier [7,8] reported that the body actively changed the lower limb strategy while wearing minimalist shoes, i.e., increased step rates, lowered foot inclination angle at foot strike and reduced knee maximum flexion angle and joint range of motion (ROM). Moreover, according to the equation for the knee joint angle and the patellofemoral joint contact area, a decreased knee ROM decreased the patellofemoral joint contact area during the stance phase of runners wearing minimalist shoes; this condition is adverse to the reduction of PFJS. By contrast, runners with high-MI shoes showed a considerably smaller knee extension moment during the propulsive phase, which substantially reduced PFCF and, eventually, the PFJS decreased by 10.4%. Furthermore, we explored the characteristics of PFCF and PFJS during the entire stance phase with minimalist shoes. Findings showed that in the 0–20% stance phase (braking phase), the curves were coincident on different shoe conditions (Figure 4), and the differences between the two shoes mostly occurred from 20% to 100% of the stance phase. First, the initial 20% of the stance phase is the braking phase. At this phase, the lower limbs were subjected to the impact of the ground, and the vGRF reached the FP (impact force). The results of the current study showed no significant difference in the impact or propulsive force (SP of vGRF) between the low- and high-MI shoes. The braking phase accounts for 1/4 of the entire stance phase, and this study suggests that wearing high-MI shoes is beneficial for decreasing knee load in the propulsive phase (20–100%). According to recent research supporting barefoot running, running shoes not only reduce the impact force and loading rate and filter high-frequency impact signals [22] but also provide different neural inputs to the lower limbs, resulting in different responses and changes in the lower limb strategy [23]. As shown in this study, the lower limbs actively changed the knee flexion angle and extension moment when the runner was wearing minimalist shoes during the propulsive phase. This phase accounts for a large proportion and may be important for reducing the patellofemoral joint loads.

Using the rating scale for minimalist shoes, this study compared minimalist shoes (MI = 86%) with cushioned shoes (MI = 26%) to further explore the relationship between knee joint load and the MI. Esculier [8] tested shoes with different MI with regards to running mechanics and observed that a higher MI shoe indicates a low foot inclination angle at foot strike and a low peak PFCF. Sinclair [7] compared minimalist, cushioned and maximalist shoes in terms of patellofemoral kinetics and observed that the knee ROM decreased when the runner was wearing minimalist shoes. Interestingly, the patellofemoral joint loads were greater with the low-MI shoes, i.e., maximalist shoes, than with the others. The above findings are similar to the results of this study. Shoes with low MI caused no reduction in the patellofemoral joint loading despite the thick midsole. By contrast, the neural inputs caused by the cushioning midsole resulted in a reduced limb movement strategy with increased knee flexion angle and knee extension moment, which may increase the risk of knee joint load and PFPS.

In previous studies, subjects were recruited regardless of their foot strike patterns and researchers failed to rule out runners who had experience with wearing minimalist shoes [13]. More than 70% of long-distance runners adopt the heel strike pattern [24,25]. Horvais noted that heel strikers use the midfoot or forefoot strike pattern during the adaptation process when wearing minimalist shoes for the first time [26]. In the current study, the vGRF graph showed two peaks, and the foot inclination angle at the point of foot strike was positive. Therefore, the runners still used the heel strike pattern after wearing the minimalist shoes [27], but the foot inclination angle at the point of foot strike still reduced by 35.6%.

Furthermore, adopting the heel strike pattern while wearing minimalist shoes on hard ground would cause heel pain. The runners who are used to rearfoot running have difficulties in switching to forefoot strike immediately when wearing minimalist shoes for a short distance. Correspondingly, runners will actively attempt to use the midfoot or forefoot strike pattern to avoid pain (various reasons lead to changes in foot strike patterns when transitioning to minimalist shoes) during longer running distances [28]. Numerous studies have shown that the reduced PFCF and PFJS in forefoot strike running can also reduce knee loads and PFPS [16,21,29]. Therefore, the analysis of the long-term effects of switching to high-MI running shoes on patellofemoral joint loads still needs to be confirmed.

In general, an adaptive process occurs when we first wear high-MI shoes. Wearing high-MI shoes, e.g., minimalist shoes, is similar to barefoot running, which has certain requirements (increased strength of the plantar muscles) [30]. Lieberman [31] stated that the function of the foot in human evolution is to adapt to barefoot walking or running, and humans began wearing cushioned shoes only in the last hundred years. Thus, the biomechanical characteristics of the foot may not be fully adapted to current cushioned shoes. The plantar muscles of runners who are accustomed to wearing cushioned shoes may lack strength to wear minimalist shoes for a long period, consequently resulting in fatigue and foot injury. Meanwhile, minimalist shoes change the runner's strike patterns to the forefoot, which requires increased calf triceps strength [32]. Therefore, in switching to high-MI shoes, the runner should gradually increase the duration of running in minimalist shoes based on previous running time and distances, thereby gradually improving the related muscle strength and the lower limb/foot adaptability.

Several limitations should be considered in this investigation that could be addressed in follow-up studies. First, we only considered the immediate shoe influence on patellofemoral joint loads. Therefore, the assessment of knee muscle forces or activation was warranted to provide further evidence of neuro-musculoskeletal reactions. Second, a long-term effect of wearing different MI shoes and the gender effects should ideally be taken into account. Finally, one should be cautioned that the differences in leg length were not considered in this study.

5. Conclusions

Patellofemoral joint loads during running were immediately changed by wearing shoes with different Minimalist Index (MI). In particular, while maintaining similar running velocity, wearing high-MI shoes significantly decreased patellofemoral contact force (PFCF) and patellofemoral contact stress (PFJS)—compared with those with low-MI shoes—by reducing the knee extension moment. This condition effectively reduced the loads on the patellofemoral joint during the mid-stance phase of running, thereby possibly reducing the risk of patellofemoral pain syndrome (PFPS).

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Conflicts of Interest: The authors declare no conflict of interest.

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