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Biomechanics of running with rocker shoes

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ABSTRACT

Objectives: Load reduction is an important consideration in conservative management of tendon overuse injuries such as Achilles tendinopathy. Previous research has shown that the use of rocker shoes can reduce the positive ankle power and plantar flexion moment which might help in unloading the Achilles tendon. Despite this promising implication of rocker shoes, the effects on hip and knee biomechanics remain unclear. Moreover, the effect of wearing rocker shoes on different running strike types is unexplored. The aim of this study was to investigate biomechanics of the ankle, knee and hip joints and the role of strike type on these outcomes.
Design: Randomized cross-over study.
Methods: In this study, 16 female endurance runners underwent three-dimensional gait analysis wearing rocker shoes and standard shoes. We examined work, moments, and angles of the ankle, knee and hip during the stance phase of running.
Results: In comparison with standard shoes, running with rocker shoes significantly ($p < 0.001$) reduced the positive (16%), and negative (32%) work at the ankle joint. Plantar flexion moment peak and impulse were also reduced by 11% and 12%, respectively. Reduction in these variables was almost two times larger for midfoot strikers than for rearfoot strikers. At the knee joint running with rocker shoes significantly increased the positive work (14%), extension moment peak (6%), and extension moment impulse (12%).
Conclusions: These findings indicate that although running with rocker shoes might lower mechanical load on the Achilles tendon, it could increase the risk of overuse injuries of the knee joint.

1. Introduction

To date, several studies have investigated the effects of using rocker (bottom) shoes on biomechanics of walking and running.[1–3] A common finding of these studies is that wearing rocker shoes, either custom-made[2,3] or commercially produced,[1,4] could result in significant changes in foot and ankle biomechanics.

Rocker shoes can produce alterations in ankle biomechanics especially during the push-off phase of gait. Among these changes are a reduction in plantar flexion moment (PFM), and ankle power generation. The Achilles tendon is subjected to repetitive mechanical overload during running activities which can exceed eight times body weight per step.[5] The triceps surae produce the PFM during push off,[6] and they are the main contributors to the power, needed for forward acceleration of the body.[7,8] Based on inverse dynamics calculations, it is estimated that the force in the Achilles tendon is proportional to the PFM created by triceps surae muscles.[5,9] In running, the peak force within the Achilles tendon occurs at the start of push-off, the same time as the peak PFM.[5,9] It has been proposed that reduced PFM and ankle power generation per step can cumulatively contribute to significant reduction in Achilles tendon load.[1,10] Load management is an important step in conservative treatment of tendinopathies which not only helps to relieve pain but also allows for tendon adaptation. From a clinical point of view, therefore, wearing rocker shoes might be valuable in treatment of Achilles tendinopathy.[1,10]

Although more attention has recently been paid to these aforementioned aspects of rocker shoes in running activities, knowledge is still limited in this area. The results of a recent study[2] have shown that (slow) running with rocker shoes caused a significant decrease in maximum power generation at the ankle joint. Since the running speed was kept constant in that study; the reduction in the ankle

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power should potentially result in a compensation in lower limb kinetic chain (i.e. increase of power generation at the knee/hip). This relation, however, was not examined.[10] Another explanation might be the simultaneous reduction of the ankle power at both generation and absorption phases of running. In fact, in a previous study on rocker shoes (Masai Barefoot Technologies), it was found that ankle power (both generation and absorption) was reduced by rocker shoes compared with a standard shoe, whereas knee power was increased.[1] In that study, however, running speed was not similar between the shoe conditions (i.e. lower speed for rocker shoes). The compensatory increase in mechanical work at the knee and hip joints can place them at risk of overuse injuries. Hence, the first aim of this study was to further investigate the knee and hip biomechanics during stance phase of running with rocker shoes. We hypothesized that decreased work at the ankle will be accompanied by increased work at the knee and/or hip joints.

In the second part of this study, we conducted an exploratory analysis on the influence of various strike patterns on running biomechanics with rocker shoes. While the majority (around 75–89%) of runners at elite and recreational level adopts a rearfoot strike pattern, some runners have a midfoot and forefoot strike type.[11] Running biomechanics differ among these landing types. For instance, runners with a non-rearfoot strike have a greater PFM and higher load on their Achilles tendon compared with rearfoot strikers.[12] The capability of rocker shoes in reducing peak and impulse of PFM (Achilles tendon loading parameters) was previously reported only for the rearfoot strikers.[2] Our aim was, therefore, to examine whether rocker shoes could influence such parameters in a similar way for other strike types (e.g. midfoot or forefoot strike). This information can provide an initial insight into implications of rocker shoes for different running styles.

2. Methods

This study was part of a larger research project designed to determine if different running shoes could be biomechanically beneficial or detrimental for running overuse injuries.[13,14] For the whole project, we decided to study females because of the higher incidence rate of stress fractures reported for this gender[15] and to eliminate gender differences in running mechanics.[16]

Two local track and field clubs were contacted to recruit experienced female endurance runners. The other inclusion criteria were: age between 18 and 55 years, regular long-distance training (running for at least 10 km/week for a minimum of 5 km per session), and no history of self-reported severe musculoskeletal injuries in the lower extremity that could affect running performance at the time of measurement. The local Medical Ethics Committee approved the experimental protocol of this study (METc 2012.014), and all participants gave written informed consent.

Two types of shoes were compared in this study: standard running shoes as the baseline condition, and rocker shoes as intervention. Rocker shoes were from the same brand and model as standard shoes with the difference that they had a stiffened rocker profile added to them by a certified orthopedic shoe technician (supplementary). The location of the apex (rolling point) of rocker shoes was proximal to metatarsal region at 53% of the shoe length.[17] The apex of standard shoes was located at 65% of the shoe length. The rocker profile thickness for different sizes was on average 2.2 ± 0.1 cm at the apex and under the heel. Depending on shoe size a pair of standard running shoes weighed on average 541 ± 44 g, and a pair of rocker shoes 858 ± 96 g.

A balanced two-way crossover design was used in which participants were randomly assigned to the two sequences of shoe conditions (in sequence 1 rocker shoes used first, and in sequence 2 control shoes used first). Participants were accustomed to the shoes as they had run on a treadmill (Valiant®; Lode, B.V., Groningen, The Netherlands) for 9 min with each pair of shoes. The evaluation of lower limb motion was based on Vicon® lower body Plug-in-gait model. Reflective markers were placed bilaterally on the anterior superior iliac spine, posterior superior iliac spine, lateral thigh, lateral femoral epicondyle, lateral shank, and lateral malleolus on the surface of the shoes at the location of the calcaneus and the second metatarsal head. During the measurements markers were tracked by an eight-camera motion capture system (Vicon®, Oxford, UK, $f_S = 200$ Hz) to measure the kinematic data. A pair of flexible pressure insoles (Pedar®, Novel GmbH, Munich) was fitted in the shoes for the measurement of plantar pressure (to determine the strike pattern).

Testing was performed on a 22 m runway with two force plates (Bertec Corporation, Columbus, Ohio, $f_S = 2000$ Hz) embedded in the middle of it. During the measurement, we monitored the speed using two photo-cells positioned 1.5 m before and after the force plates. Before the data collection, participants performed 5 running trials along a 22-m runway at their self selected speed to determine their comfortable speed. Participants were then positioned in a way that they would make a full foot contact on the force plate with their dominant foot (defined as the foot they would kick a ball with). A trial was accepted if the participant hit the force plate completely and the speed was within 5% of determined comfortable speed. Moreover, a trial was repeated if the assessor had the impression that participant had targeted the fore plate. After collecting five acceptable trials, the same procedure with the other shoes was carried out.

Power (W/kg), internal moment (Nm/kg), and angle (degree) of the ankle, knee and hip joints in the sagittal plane were determined for the dominant limb using the Vicon Plug-In-Gait model. Joint power was calculated as the product of net joint moment and joint angular velocity. A customized Matlab™ script was used to further process these data. Kinetic data was filtered using a 4th order Butterworth low-pass filter with a cut-off frequency of 10 Hz. The data were time normalized to 100% of stance phase using a linear interpolation and normalized for body mass (kg). The stance phase was defined as the period between initial ground contact (vertical ground reaction force exceeded 10 N) and toe-off (vertical ground reaction force dropped below 10 N). Kinematic and force plate data were used to calculate the time–distance parameters.

To identify the strike pattern, we used the data gained from an in-shoe plantar pressure system (Pedar®, step-analysis software). We only analyzed the data of the dominant limb. First we excluded the first 25% of steps (acceleration) and the last 25% of steps (deceleration) of the recorded steps in each trial. For the remaining steps of each trial (ranged from 3 to 5 steps), the location of the center of pressure at initial contact in anterior-posterior direction (CoP-AP, mm) was determined. This parameter was then normalized to the insole length (mm). The location proximal to 33% of the insole length was defined as rearfoot strike; the location between 33% and 67% was defined as a midfoot strike; and the location distal to 67% was defined a forefoot strike.[18]

Work (positive, negative and net, J/kg) done at the ankle, knee and hip joints was analyzed as our primary outcome. Work values were calculated as the areas under the power–time curves in stance without normalization. The total network was also calculated as the summation of network values of the ankle, knee and hip joints. In order to have a more complete picture of biomechanical adaptations in the lower extremity, we analyzed several additional parameters including joint moments and angles as well as time–distance parameters. Regarding the joint moments, the maximum value (peak, Nm/kg) and moment over time (impulse, Nm s/kg) were assessed for the ankle plantar flexion, knee extension and hip flexion. Moment impulse was calculated as the area under the PFM–time curve in stance without normalization.

Table 1
Mean [95% confidence interval] of kinetics, kinematics and time-distance parameters.

Variables	Standard shoe	Rocker shoe	Difference	p-value[e]
Joint work (J/kg)				
Ankle				
Positive	0.988 [0.885; 1.09]	0.830 [0.725; 0.935]	0.158 [0.0934; 0.223]	<0.001
Negative	0.537 [−0.632; −0.442]	0.364 [−0.456; −0.274]	0.173 [−0.230; −0.115]	<0.001
Net	0.451 [0.377; 0.525]	0.465 [0.391; 0.540]	−0.0143 [−0.0561; 0.0275]	0.476
Knee				
Positive	0.662 [0.530; 0.793]	0.754 [0.622; 0.886]	−0.0923 [−0.133; −0.0517]	<0.001
Negative	0.802 [−0.915; −0.689]	0.843 [−0.957; −0.729]	−0.0412 [−0.0188; 0.101]	0.163
Net	−0.140 [−0.211; −0.0687]	−0.0888 [−0.154; −0.0241]	−0.0511 [−0.0981; −0.00399]	0.036
Hip				
Positive	0.0678 [0.00932; 0.126]	0.127 [0.0557; 0.199]	−0.0595 [-0.136; 0.0170]	0.117
Negative	0.545 [−0.731; −0.359]	0.524 [−0.724; −0.324]	0.0212 [−0.118; 0.0757]	0.647
Net	−0.477 [−0.675; −0.280]	−0.397 [−0.603; −0.191]	−0.0806 [−0.133; −0.0284]	0.005
Total Net Work	−0.166 [−0.375; 0.0431]	−0.0201 [−0.242; 0.202]	−0.146 [−0.255; −0.0374]	0.012
Joint moment[a] peak (Nm/kg)				
Ankle plantar flexion	3.32 [3.03; 3.60]	2.96 [2.68; 3.23]	0.356 [0.199; 0.514]	<0.001
Knee extension	2.70 [2.31; 3.08]	2.86 [2.46; 3.25]	−0.160 [−0.281; −0.0391]	0.013
Hip flexion	1.55 [1.08; 2.01]	1.51 [1.08; 2.00]	0.0388 [−0.181; 0.258]	0.710
Joint moment[a] impulse (Nm s/kg)				
Ankle plantar flexion	0.415 [0.378; 0.451]	0.363 [0.328; 0.399]	0.0514 [0.0325; 0.0702]	<0.001
Knee extension	0.289 [0.245; 0.333]	0.323 [0.278; 0.368]	−0.0340 [−0.0489; −0.0195]	<0.001
Hip flexion	0.126 [0.0699; 0.183]	0.110 [0.0517; 0.169]	0.0163 [0.00429; 0.0283]	0.011
Joint angle (°)				
Ankle[b]				
Initial contact	11.3 [5.70; 17.0]	12.9 [7.26; 17.5]	−1.53 [−3.56; 0.491]	0.127
Peak dorsiflexion	29.8 [26.9; 32.7]	27.6 [24.8; 30.4]	2.18 [0.650; 3.72]	0.009
Toe-off	−12.8 [−15.6; −9.89]	−12.1 [−14.9; −9.32]	−0.658 [−1.75; 0.429]	0.215
Knee[c]				
Initial contact	19.3 [16.4; 22.2]	19.0 [16.0; 22.0]	0.323 [−0.742; 1.388]	0.526
Peak flexion	48.5 [45.5; 51.5]	49.1 [46.0; 52.1]	−0.576 [−1.47; 0.321]	0.190
Toe-off	12.0 [9.00; 15.1]	13.5 [10.2; 16.7]	−1.44 [−3.05; 0.177]	0.077
Hip[d]				
Initial contact	38.0 [33.5; 42.5]	38.1 [33.6; 43.0]	−0.0760 [−0.973; 0.821]	0.860
Toe-off	−9.05 [−12.7; −5.39]	−6.18 [−9.90; −2.45]	−2.87 [−3.82; −1.92]	<0.001
Speed (m/s)	3.33 [3.09; 3.57]	3.34 [3.10; 3.59]	−0.0188 [−0.0551; 0.0257]	0.449
Stance time (s)	0.237 [0.222; 0.252]	0.231 [0.216; 0.246]	0.00620 [0.00159; 0.0108]	0.012
Step time (s)	0.382 [0.369; 0.395]	0.383 [0.370; 0.399]	0.00312 [−0.00908; 0.00529]	0.660
Step length (m)	1.22 [1.13; 1.32]	1.26 [1.16; 1.36]	−0.0340 [−0.0999; 0.0319]	0.287
Step frequency (step/s)	2.63 [2.54; 2.73]	2.63 [2.54; 2.72]	0.00774 [−0.0383; 0.0538]	0.724

[a] Moments are internal joint moments.
[b] A positive angle denotes dorsiflexion and a negative angle plantar flexion.
[c] A positive angle denotes flexion.
[d] A positive angle denotes flexion and a negative angle extension.
[e] The statistical significance level was set at $p < 0.05$.

For the ankle, knee and hip, the joint angles (degree) at initial contact, and toe-off were examined. The maximum angles at ankle (peak dorsiflexion) and knee (peak flexion) were examined as well. Speed (m/s), stance time (s), step time (s), step length (m), and step frequency (step/s) were the studied time–distance parameters, calculated from kinematic and force plate data.

Descriptive statistics were used to describe the characteristics of the study population. For each participant the data of the five trials were averaged for each shoe condition. A linear mixed model was fitted with SAS software, version 9.3 (SAS Institute, Inc., Cary, North Carolina) to estimate the shoe effect. The model contained the fixed effects for shoe (treatment), sequence (order of the shoes), and period (order of time). An effect of sequence could indicate an unequal carry-over effect from one shoe to the other shoe, which would complicate the estimate of the treatment effect. An effect of period may indicate familiarization to the study procedure and it is included to obtain an unbiased estimate of the treatment effect. The covariance structure for the repeated observations was taken unstructured. Additionally, the participants habitual strike pattern (as determined during running with the normal shoe) was included in the model to investigate if the effect of rocker shoes would depend on the strike pattern. Type III tests were used to determine the shoe effect, and the level of significance was set at $p < 0.05$.

3. Results

Eighteen runners participated in this study. Due to missing markers, we excluded two participants. Sixteen runners were finally included for the analysis with the following characteristics (mean ± SD): age = 24 ± 3 years, height = 171 ± 6 cm, and weight = 62 ± 8 kg. The analysis showed that there were no sequence or period effects for any of the examined parameters.

Running with rocker shoes caused a reduction of 16% in the positive work (power generation) (0.16 J/kg, $p < 0.001$), and a reduction of 32% in the negative work (power absorption) (0.17 J/kg, $p < 0.001$) at the ankle. Net work at the ankle remained unchanged ($p = 0.476$). At the knee joint the positive work and network increased with rocker shoes by 14% (0.092 J/kg, $p < 0.001$) and 19% (0.051 J/kg, $p = 0.036$), respectively, while the negative work remained unchanged ($p = 0.163$). At the hip joint, the network was the only variable which was affected by rocker shoes with a reduction of 17% (0.081 J/kg, $p = 0.005$) for this variable. When looking

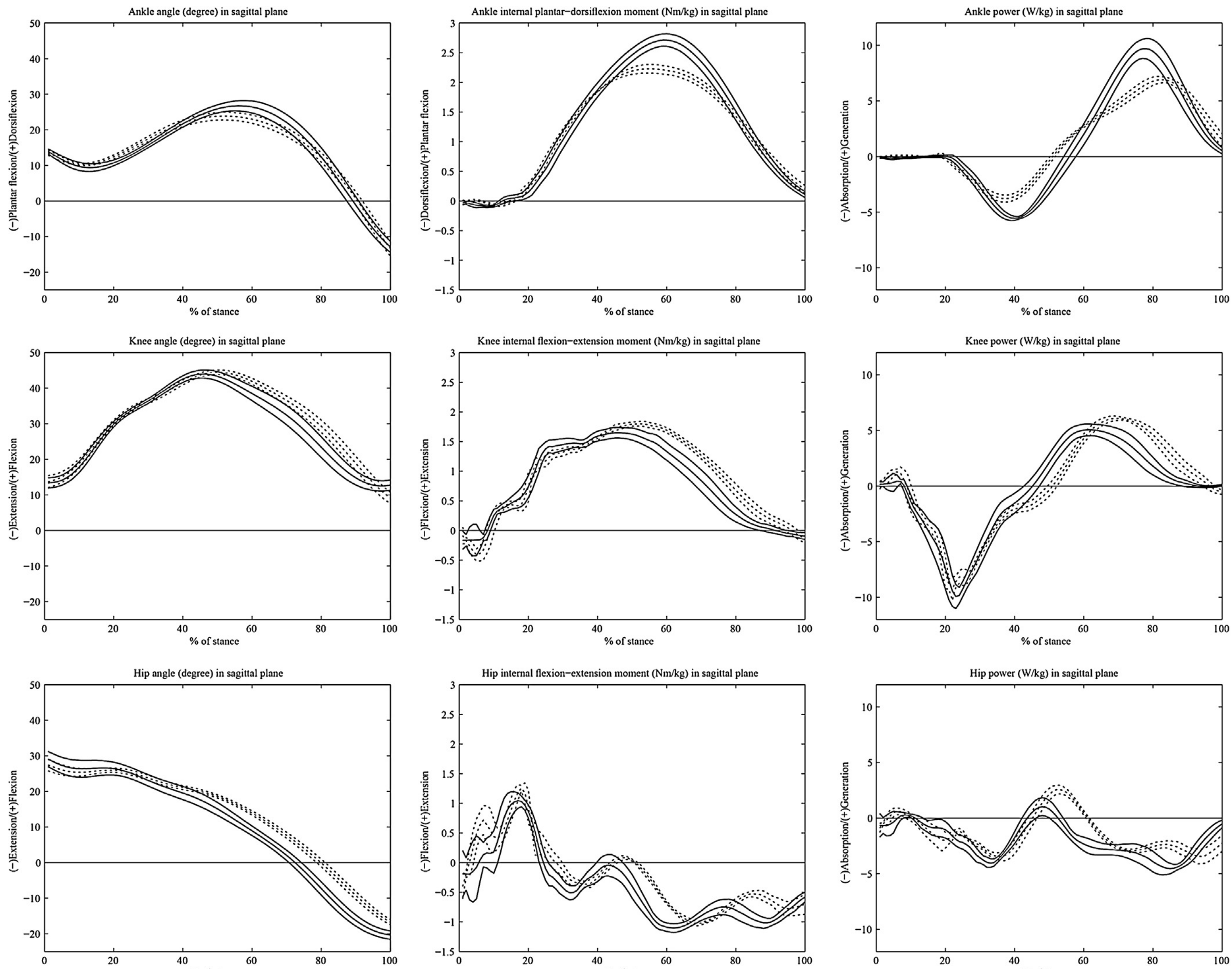

Fig. 1. Sagittal plane joint angle (left panels), moment (middle panels) and joint power (right panels) at the ankle (top panels), knee (middle panels) and hip (bottom panels) for the stance phase of running. The curves are mean and standard deviation of five trials of one participant when running with standard (—) and rocker shoe (- - -).

at the total network, rocker shoes caused 0.146 J/kg reduction ($p = 0.012$) in comparison with standard shoes.

Regarding the joint moments, running with rocker shoes significantly ($p < 0.001$) decreased PFM peak by 11% (0.36 Nm/kg) and PFM impulse by 12% (0.051 Nm s/kg). The peak and impulse of the knee extension moment were significantly increased by 6% (0.16 Nm/kg, $p = 0.013$) and 12% (0.034 Nm s/kg, $p < 0.001$), respectively when running with rocker shoes. While there was no difference in peak hip flexion moment ($p = 0.710$) between two shoes, the hip flexion moment impulse was significantly decreased by 13% (0.016 Nm s/kg, $p = 0.011$) with rocker shoes.

The only significant change in kinematics was observed in the ankle joint where rocker shoes decreased the peak dorsiflexion by 7% (2.18°, $p = 0.009$). The only difference in time–distance parameters was a 3% shorter stance time with rocker shoes (0.006 s, $p = 0.012$) compared with standard shoes. Table 1 summarizes the statistical analyses for all outcome variables. In addition, a graphical representation of power, moment and angle curves of the lower extremity is shown in Fig. 1.

Based on CoP-AP data of standard shoes, 10 runners were classified as habitual rearfoot striker and 6 runners as midfoot striker. For the ankle joint, the mixed model revealed an interaction between the shoe type and the strike pattern for positive and negative work as well as PFM peak and impulse. While the direction of the changes in these variables was the same for rearfoot and midfoot strikers (i.e. reduction with rocker shoes), the effect sizes were almost two times larger for midfoot strikers (Table 2).

4. Discussion

The main aim of this experiment was to study lower limb biomechanics during running in rocker shoes. Previous studied found that running with rocker shoes could considerably decrease the plantar flexion moment and power generation at the ankle joint. We hypothesized that runners would employ compensatory strategies at the knee and/or hip joints in response to reduced mechanical work at the ankle.

Similar to previous studies, the ankle joint was the main source of positive work in overground running.[19,20] The values of ankle work (positive and negative) were similar to those reported by Pires et al.[21] The rocker shoe reduced both positive and negative work done by the ankle. Since rocker shoes proportionally decreased positive (0.16 J/kg) and negative (0.17 J/kg) work, net mechanical work at the ankle remained unchanged. In the current study, peak PFMs for the standard (3.32 Nm/kg) and rocker shoes (2.96 Nm/kg) were higher in magnitude compared with a previous

Table 2
The interaction between shoe and strike type separately for rearfoot and midfoot strikers. The numbers are mean differences [95% confidence interval] between standard shoes and rocker shoes.

Variables	Rearfoot strike ($n=10$) (Standard – Rocker)	Midfoot strike ($n=6$) (Standard – Rocker)	p-value[e]
Joint work (J/kg)			
Ankle			
Positive	0.111 [0.0403; 0.181]	0.240 [0.147; 0.333]	0.034
Negative	−0.116 [−0.161; −0.0713]	−0.273 [−0.329; −0.211]	<0.001
Net	0.00412 [−0.0487; 0.0570]	−0.0461 [−0.115; 0.0230]	0.508
Knee			
Positive	−0.0740 [−0.126; −0.0220]	−0.124 [−0.193; −0.0556]	0.234
Negative	0.0227 [−0.0561; 0.102]	0.0732 [−0.0320; 0.178]	0.427
Net	−0.0539 [−0.112; 0.00386]	−0.0462 [−0.119; 0.0269]	0.854
Hip			
Positive	−0.0683 [−0.149; 0.0124]	−0.0441 [−0.135; 0.0466]	0.558
Negative	−0.0233 [−0.139; 0.0921]	−0.0174 [−0.160; 0.125]	0.940
Net	−0.104 [−0.161; −0.0463]	−0.0406 [−0.106; 0.0251]	0.060
Total Net Work	−0.148 [−0.274; −0.0215]	−0.143 [−0.296; 0.0100]	0.956
Joint moment[a] peak (Nm/kg)			
Ankle plantar flexion	0.234 [0.0741; 0.394]	0.567 [0.356; 0.779]	0.018
Knee extension	−0.118 [−0.274; 0.0375]	−0.232 [−0.434; −0.0309]	0.343
Hip flexion	−0.0240 [−0.290; 0.241]	0.147 [−0.197; 0.492]	0.404
Joint moment[a] impulse (Nm s/kg)			
Ankle plantar flexion	0.0362 [0.0176; 0.0550]	0.0775 [0.0528; 0.102]	0.013
Knee extension	−0.0326 [−0.0517; −0.0135]	−0.0366 [−0.0616; −0.117]	0.785
Hip flexion	0.0157 [0.00178; 0.0297]	0.0173 [0.000297; 0.0342]	0.865
Joint angle (°)			
Ankle[b]			
Initial contact	−0.143 [−2.41; 2.13]	−3.93 [6.68; 21.3]	0.052
Peak dorsiflexion	1.36 [−0.431; 3.16]	3.60 [1.24; 5.96]	0.128
Toe-off	−0.848 [−2.21; 0.516]	−0.332 [−2.11; 1.44]	0.624
Knee[c]			
Initial contact	−0.277 [−1.50; 0.951]	1.36 [−0.248; 2.97]	0.103
Peak flexion	−0.890 [−2.04; 0.260]	−0.0326 [−1.56; 1.49]	0.358
Toe-off	−1.94 [−3.97; 0.0950]	−0.576 [−2.46; 9.03]	0.381
Hip[d]			
Initial contact	0.0781 [−1.10; 1.26]	−0.342 [−1.91; 1.22]	0.656
Toe-off	−2.97 [−4.20; −1.73]	−2.71 [−4.32; −1.09]	0.790
Speed (m/s)	−0.00769 [−0.0597; 0.0444]	−0.0267 [−0.0951; 0.0417]	0.641
Stance time (s)	0.00827 [0.00247; 0.0141]	0.00262 [−0.00512; 0.0104]	0.240
Step time (s)	−0.00396 [−0.0124; 0.00450]	0.00302 [−0.00816; 0.0142]	0.389
Step length (m)	−0.0529 [−0.134; 0.0279]	−0.00131 [−0.107; 0.104]	0.413
Step frequency (step/s)	−0.0256 [−0.325; 0.0837]	−0.0231 [−0.100; 0.0538]	0.300

[a] Moments are internal joint moments.
[b] A positive angle denotes dorsiflexion and a negative angle plantar flexion.
[c] A positive angle denotes flexion.
[d] A positive angle denotes flexion and a negative angle extension.
[e] The statistical significance level was set at $p<0.05$.

observation (standard shoe = 1.73 Nm/kg and rocker shoe = 1.49).[2] This increase in the ankle moment can be explained by the difference in running speeds between the two studies (3.3 ms in this study versus 2.5 ms in the previous study).[2] Kinematically, we found decrease in dorsiflexion angle which is in line with previous reports.[1,2] As previously mentioned in the methods section, joint power was calculated as the product of joint moment and joint angular velocity. PFM was reduced when wearing rocker shoes at approximately 40–80% of the stance phase (Fig. 1). Regarding our research question, therefore, the changes in ankle power output with rocker shoes are not thought to be influential on running speed as rocker shoes reduce energy absorption and generation almost equally at the ankle level. In addition, the total network was negative for both shoes meaning that the work done by the stance leg is used more for power absorption than generation during level running. Considering the possibility of energy transfer between upper limb, lower limbs and center of mass,[22] it can be speculated that part of positive work might be generated by the swing leg, upper extremities or trunk in order to propel the body forward.

The kinetic and kinematic changes that occurred at the ankle joint with the rocker shoe could have clinical advantages in the load management of the Achilles tendon. The reductions in ankle power generation and absorption indicate lower force generated by the triceps surae during both the breaking (eccentric control of forward rotation of the leg) and propulsion phases (push-off) of running. Using magnetic resonance imaging it is shown that the Achilles tendon has a shorter moment arm in dorsiflexion positions compared to plantar flexion positions.[23] This suggests that the triceps surae should produce larger forces at dorsiflexion positions than plantar flexion for equal joint moments. Since the peak dorsiflexion angle was reduced with rocker shoes, it can be helpful to reduce the force acting on the Achilles tendon as well.

Following the ankle, the knee and hip joints were observed to be the second and third contributors to the total power/work done in running. Some researchers reported similar results.[19,20] However, while we observed both positive and negative work at the knee joint, another study reported only negative work.[21] This discrepancy in the knee joint power/work might be attributed to the inherent differences between overground running (current study) and treadmill running (previous study). A significant reduction in knee power generation during treadmill running in comparison with overground running has been already reported.[24] We found very little change for the kinematic parameters at the knee and hip joints. As we mainly checked the joint angles at initial contact and toe-off, it could be that the sole of rocker shoes has limited effects on joint kinematics at these discrete time points.

While running in rocker shoes, positive work was increased at the knee joint without significant changes in hip positive work. Running in rocker shoes also caused an increase in the peak (6%) and impulse (12%) of the knee extension moment. The increase in internal knee extension moment is probably caused by the proximal apex of rocker shoes shifting the application point of the ground reaction force vector posterior to the knee joint. This effect might place the knee joint at risk of overuse injuries, and further investigation is needed to identify the exact mechanism and strategies to minimize such negative effect. In terms of running energetics, however, this change in the knee moment might have a positive side too. A recent study has shown that more economic runners have less reliance on the ankle for both generation and absorption and greater reliance on the knee for energy generation.[25] As the rocker shoes change running biomechanics in a similar way, this could reduce the energy cost compared to the standard shoes. However, in a previous study,[26] it was found that running with rocker shoes significantly increased the energy expenditure during sub-maximal running when compared with standard and minimalist running shoes. Since the shoes were not matched for weight in that study (rocker shoes were heavier), and we know that extra mass of the shoe is negatively influential on running economy,[27] it is worthwhile to perform a similar study and see how running with rocker shoes would affect aerobic demand of running after correcting of the shoe mass.

Our primary assumption in this study was that the overall effect of rocker shoes on running biomechanics would be independent of the strike type. For this reason strike type was not considered as an inclusion criterion. However, it might be possible that the effect size would be different for different strike types. Such interaction was indeed found at the ankle joint despite the small sample sizes of the two subgroups identified in our study (rearfoot versus midfoot strikers). While the positive and negative work as well as PFM parameters were significantly reduced by rocker shoes in both rearfoot and midfoot striker groups; the magnitude of reduction was almost double for midfoot strikers (see Table 2). Keeping a midfoot landing pattern with rocker shoe (with an apex positioned proximal to metatarsal region) might make running unstable and it is likely that rocker shoes could have changed midfoot strikers to rearfoot strikers. Closer examination of plantar pressure data confirmed our assumption for all six midfoot runners. It is known that non-rearfoot strikers demonstrate greater plantar flexion moment compared to rearfoot strikers.[28] For midfoot strikers, therefore, part of the shoe effect in this study might be caused by a change in strike pattern. Based on this finding, it can be speculated that midfoot strikers might benefit even more from the effects of a rocker shoe on Achilles tendon load than rearfoot strikers.

There are several limitations to the current study. First, we limited our analysis to the stance phase of running. The extra mass of rocker shoes could change the inertial characteristics of the lower limb. Although this has little effect upon stance phase, it could considerably influence lower limb function during swing phase of gait.[29] Moreover, we only studied the biomechanical changes in the sagittal plane. Although power generated and absorbed in non-sagittal planes are relatively low compared to the sagittal plane,[20] more information in this regard could be insightful. In the second part of study we could only identify 6 runners with a midfoot strike pattern. Therefore, the generalizability of findings as well as statistical power of this part of study is limited. The rocker shoes used in this investigation were manufactured by a certified orthopedic shoe technician. It would be informative to repeat similar experiments using commercially available rocker shoes. Finally, we only evaluated rocker shoe biomechanics after a short adaptation time, and therefore, their biomechanical efficacy after a longer period of use is unknown.

5. Conclusion

Running with rocker shoes reduces both positive and negative work as well as PFM at the ankle, which indicates less force produced by triceps surae muscles and consequently lower mechanical loads on the Achilles tendon. This effect is more prevalent for runners with a midfoot strike pattern. Running with rocker shoes increases mechanical work at the knee joint as well.

Hence, while rocker shoes have the capacity to reduce load on the Achilles tendon they might increase the risk of knee overuse injuries.

Practical implications

- Running with rocker shoes might help to decreases the load on the Achilles tendon.
- Running with rocker shoes might increase the risk of overuse injuries of the knee joint.
- Midfoot strike runners seem to benefit more from the effects of a rocker shoes than rearfoot strikers.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jsams.2016.04.008.

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