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Redistribution of knee and ankle joint work with different midsole thicknesses in non-rearfoot strikers during running: a cross-sectional study

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Purpose: The aim of this work was to i nvestigate the effects of midsole thickness on non-rearfoot strike runners' redistributions of knee and ankle joint negative and positive work. *Methods*: Fourteen healthy male runners wore minimalist, traditional and maximalist shoes and ran in a straight line in each shoe in the laboratory at a speed of 15 km/h, with a ±5% difference being allowed. Whole-body kinematics and ground reaction forces were recorded, and the data of eleven non-rearfoot strikers were used for the analysis. Ankle and knee joint negative and positive work was calculated by integrating each joint's torque power. Friedman test was used for statistical comparisons. *Results*: Running in minimalist shoes induced significantly greater ankle joint negative and positive work than in other shoes. Running in maximalist shoes induced significantly lower ankle joint positive work and greater knee joint negative work than in other shoes, and significantly greater knee joint positive work than in minimalist shoes. *Conclusions*: Our results indicated that non-rearfoot strikers redistributed joint negative and positive work from the knee to the ankle when using minimalist shoes or from the ankle to the knee when using maximalist shoes. It is recommended that future research employs more rigorous study designs, such as randomised controlled trials and longitudinal studies, to provide a more accurate assessment of the effect of these shoes on injury rates.

Key words: *maximalist shoes, minimalist shoes, biomechanics, running shoes, footwear, running, forefoot strike*

1. Introduction

Running is a fundamental exercise, and running shoes are crucial for protecting the runner's body from the impact of landing. The impact of landing on the runner's leg (quantified as the impact peak of ground reaction force [GRF]) appears to be a possible risk factor for running-related overuse injuries, such as patellofemoral pain and plantar fasciitis [18]. Therefore, selecting thicker midsoles and having shoes with greater cushioning (called "maximalist [MAX] shoes", defined as more than 30 mm heel height in this study) has been proposed to reduce the impact of landing on the leg. Conversely, the use of thinner midsole shoes that have less supporting materials (called "minimalist [MIN] shoes", defined as less than 15 mm heel height in this study) to avoid running-related injuries has also become popular [25]; nevertheless, they are still not common. Running with MIN shoes enables runners to shift to more mid/forefoot strikes [23], [27] which does not cause an impact peak (or cause less impact peak) because the impact peak arises due to the heel collision with the ground [15], [22]. Thus, the protective roles of running shoes include midsole cushioning to absorb the impact of landing (MAX shoes) and to help runners with more shock-absorbing motion (MIN shoes).

Generally, the lower limb joints are the runner's main shock absorber. The shock absorption system differs according to the foot strike pattern because mid/forefoot strikers initially contact their mid/forefoot

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region, which is anterior to the ankle joint, whereas rearfoot strikers initially contact their heel with the ground. As for the ankle joint, rearfoot strike runners attenuate the shock of heel landing via ankle plantarflexion while producing dorsiflexion torque. In contrast, non-rearfoot strike runners attenuate the shock via ankle dorsiflexion while producing plantarflexion torque. Thus, differences in foot strike patterns seem to result in the different distribution of lower limb joint shock-absorbing mechanics (i.e., joint negative work) [14], [33]. Non-rearfoot strike runners have greater ankle joint negative work and less knee joint negative work than rearfoot strike runners [14], [33]; therefore, rearfoot strikers and non-rearfoot strikers absorb the shock mainly at the knee joint and ankle joint, respectively.

Considering that non-rearfoot strike runners do not cause impact peak (or cause less impact peak) [15], [22], how does increasing the midsole thickness benefit these runners? With respect to the relationship between running shoes and running performance, heel midsole thickness may not be necessary, as the increasing midsole thickness leads to heavy shoe mass and deteriorates running economy [29]. Nevertheless, the midsole thickness in the region where the shoes first make contact with the ground is crucial for both rearfoot and non-rearfoot strikers to attenuate the impact of landing because MIN shoes increase the impact of landing on the tibia if runners (both rearfoot and non-rearfoot strikers) do not change their original foot strike patterns [16]. Accordingly, the advantage of MIN shoes seems to be shifting rearfoot strikers to non-rearfoot strikes, thereby reducing the impact peak [23], [27]. For non-rearfoot strikers who tend not to produce impact peak [15], [22], MAX shoes may be more beneficial in reducing the impact if they do not shift rearfoot strikes, even when running using MAX shoes.

As for rearfoot strikers, running with different midsole thickness changes the runners' distribution of lower limb joint negative and positive (i.e., joint propulsive energy generation) work [12]. Running with thinner midsole shoes increases the ankle joint negative and positive work, whereas running with thicker midsole shoes increases the knee joint negative and positive work in the rearfoot strike [4], [12]. Nonetheless, this redistribution of the ankle and knee joint negative and positive work may also be influenced by the changes in the participants' foot strike patterns from the rearfoot to midfoot strike [30]. Considering the greater ankle joint work [14], [33] and triceps surae muscle force/work [33], [34] in non-rearfoot strikers than in rearfoot strikers, a thicker midsole is more beneficial for non-rearfoot strikers to mitigate the load of the ankle plantar flexion muscle-tendon unit [28]. In rearfoot strikers, MAX shoes could reduce the load on the ankle plantarflexion muscle-tendon unit because of the smaller peak dorsiflexion angle during the stance phase [1]. However, little is known about the effects of differences in midsole thicknesses on the lower limb joint absorption and generation system (i.e., joint negative and positive work) in non-rearfoot strikers. Nevertheless, 5–20% of recreational runners are non-rearfoot strikers [5], [19].

Several studies have examined the effects of midsole thicknesses on lower limb joint work in rearfoot strike runners and reported that thinner midsoles induced greater ankle joint work [4], [12] and thicker midsoles induced greater knee joint work [4], [30]. However, there are only studies on rearfoot strikers. Investigating the effects of different midsole thicknesses on non-rearfoot strikers' lower limb mechanics can suggest how the running loads on non-rearfoot strikers' lower limb joints change for different midsole thicknesses. This is informative for runners and coaches to select their running shoes and for running shoe developers to design midsoles. Thus, it is necessary to investigate the effects of midsole thickness in non-rearfoot strikers.

Therefore, the current study aimed to investigate the effects of midsole thickness on the joints' shock absorption and energy generation system in non-rearfoot strike runners. The current study may offer suggestions for non-rearfoot strike runners to choose commercially available running shoes. We hypothesised that thicker midsole shoes could induce greater knee joint shock negative and positive work, whereas thinner midsole shoes could induce greater ankle joint negative and positive work. The current study tested this hypothesis by using different types of shoes – namely, MIN, traditional (TRAD) and MAX shoes.

2. Materials and methods

2.1. Research question and study design

In this study, we investigated the effects of midsole thickness on non-rearfoot strikers' knee and ankle joint work. The research questions are how non-rearfoot strikers adapt to the different midsole thicknesses and how midsole thickness affects non-rearfoot strikers' joint shock absorption and energy generation system. This is a cross-sectional study.

2.2. Participants

Fourteen healthy male runners (mean ± standard deviation: age, 20 ± 1 years; height, 173.7 ± 4.9 cm; weight, 58.3 ± 4.0 kg; leg length, 80.0 ± 3.0 cm) who had been running for at least 2 years were recruited for this study. However, three of these runners were excluded from the analysis because they exhibited rearfoot strike in the experiment (the manner of separating foot strike pattern is mentioned later). Six participants were long-distance university athletes, whereas the others were recreational runners at the same university. All participants were free from pain or injury for 1 month, had no surgical procedures in the last two years and did not run or train for 24 hours prior to measurements.

2.3. Assessment of sample size

The sample size was determined using G*Power software (G*Power software version 3.1.9.6; Dusseldorf, Germany). We conducted an *a priori* power analysis with an alpha probability of 0.05, an effect size of 0.5, and a power of 0.8. The analysis indicated that 9 subjects were required for the experiment.

2.4. Ethics

This study was approved by Doshisha University (application number: 21036) and written informed consent was obtained from the participants. We used a questionnaire to investigate age, running history, subject's injury history and amount of practice.

2.5. Footwear

For this experiment, the following three types of different midsole thickness shoes were selected: MIN shoes (XERO SHOES PRIO: stack height of 5 mm; zero drop; shoe mass of 229 g), TRAD shoes (New Balance FRESH FOAM TEMPO: heel height of 24 mm; forefoot height of 18 mm; shoe mass of 217 g), and MAX shoes (New Balance FRESH FOAM ALTOM: heel height of 35 mm; forefoot height of 25 mm; shoe mass of 228 g) (Fig. 1). Information regarding shoe height and drop was obtained from each manufacturer. Each shoe mass was measured for the size of 26.5 cm without a detachable insole. Detachable insoles were removed from all shoes to avoid the effect of different detachable insoles. To minimise the effects of different midsole materials, we chose the MAX and TRAD shoes because they were produced by the same manufacturer and used the same material (FRESH FOAM) in the midsole. To avoid the effects of different midsole materials, we also chose the MIN shoes because they had no midsole material (only the outsole and fixed insole). The participants' shoe sizes were 26.5 or 27.5 cm and these shoes were brand new. Six participants usually wore shoes close to TRAD, whereas the others usually wore shoes close to MAX.

Fig. 1. Three different types of shoes used in the current study: a) minimalist (MIN, XERO SHOES PRIO), b) traditional (TRAD, New Balance FRESH FOAM TEMPO), c) maximalist (MAX, New Balance FRESH FOAM ALTOM) shoes

2.6. Experimental setup

Three-dimensional motion data and GRF were recorded using a motion capture system (MAC 3D System, Motion Analysis, CA, Rohnert Park, USA) consisting of 10 cameras (Eagle Digital, Motion Analysis, CA, USA) and three embedded force platforms (FP4080 ×1 and FP4060 ×2, Bertec, Columbus, OH, USA). Reflective markers were mounted on the entire body (Fig. 2). The anatomical landmarks for marker positions were as follows: seventh cervical spine, suprasternal notch, seventh thoracic verte-

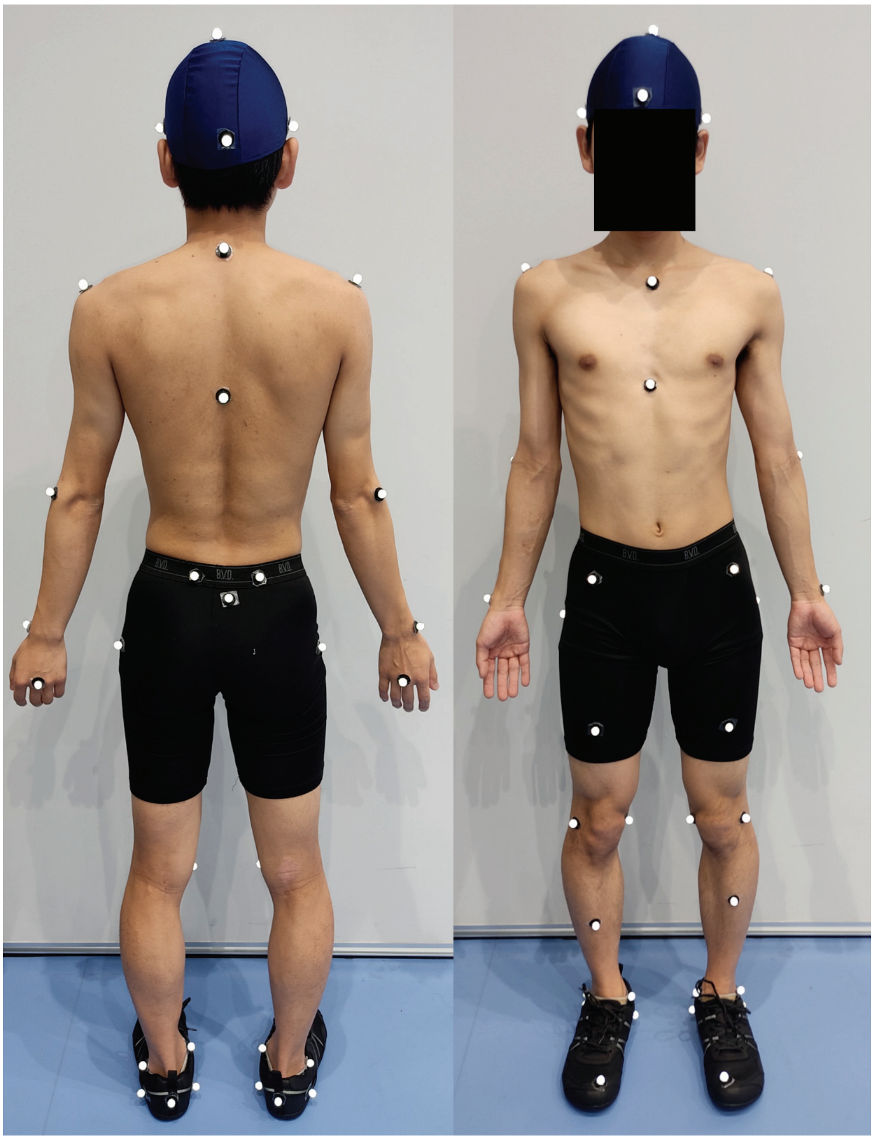

Fig. 2. Placement of reflective markers on the full body

brae, xiphoid process, acromion, lateral epicondyle of the humerus, styloid process of the radius, third metacarpal, sacrum, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, medial/lateral epicondyle of the femur, medial/lateral malleolus and calcaneal tuberosity. Additional markers were placed on the head, forehead, rear head, medial/lateral head, bilateral front thigh, bilateral front shank, bilateral medial/lateral heels and bilateral toes. The acromion, lateral epicondyle of the humerus and styloid process of the radius were substituted for the shoulder, elbow and wrist joints, respectively. The markers on the head, trunk, upper limb, and left lower limb were used only for calculating the whole-body centre of mass. We only targeted evaluation in the right lower limb joint. Marker trajectories were sampled at 240 Hz, and force platform data were sampled at 1000 Hz (resampled at 240 Hz to synchronize with kinematics data).

2.7. Validity and reliability of instruments

According to the manufacturer's nominal values, the Eagle Digital Camera (Eagle Digital, Motion Analysis, CA, USA) has a resolution of 1.3 million pixels at 1280 × 1024, full resolution at up to 500 frames per second, 1280 × 512 at 1000 frames per second, 1280 × 256 at 2000 frames per second and a processing rate of 600 million pixels per second. The force platforms (FP4080 ×1 and FP4060 ×2, Bertec, Columbus, OH, USA) have a resolution of ± 0.5 N/LSB (least significant bit). Their maximal vertical load is 5000 N, and their maximal mediolateral and anterior-posterior loads are 2500 N.

2.8. Measuring protocol

Initially, the participants ran for 5 min at a free pace on the treadmill and performed free warm-ups for 5 min in the laboratory. The warm-up was performed using their shoes. After the warm-up, reflective markers (described above) were mounted on their bodies.

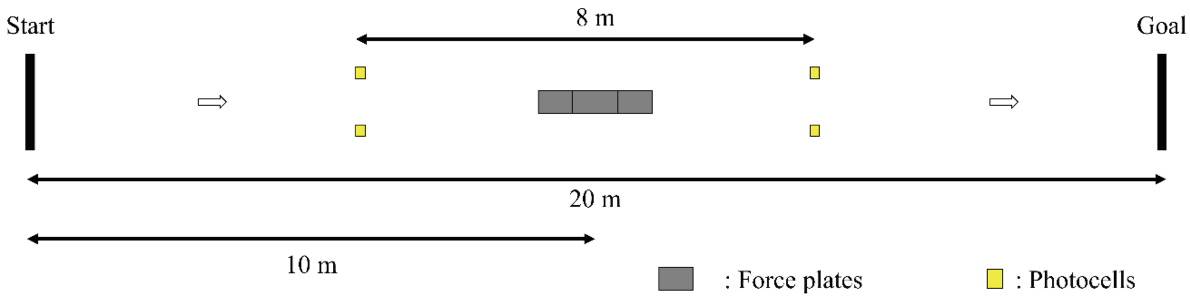

Fig. 3. The arrangement of force plates and photocells

For this measurement, the participants were required to run approximately 20 m straight at 15 km/h and to strike their right leg on one or two force platforms. All participants practised running at least five times (up to 10 times) before measurement using the respective experimental shoes. The order of shoes was randomised. Two photocells (Witty, Microgate, Bolzano, Italy) were used to determine the participants' running velocity, and a ±5% difference was allowed. Five valid trials were recorded for each shoe condition. The following trials were considered invalid trials: incorrect striking on the force platforms (foot sticking out from the force platform), running at a speed out of the set range, and/or unnaturally running, as judged by an examiner or the participants themselves. For each participant, all tests were conducted on the same day. The participants rested for at least 5 min between the different shoe conditions. The arrangement of force plates and photocells on the runway is illustrated in Fig. 3.

2.9. Outcomes

This study investigated knee and ankle shock absorption and energy generation systems. We evaluated shock absorption as negative joint work and energy generation as positive joint work in the stance phase.

2.10. Data analysis

The marker position data were processed using Cortex software version 8.00 (Motion Analysis, CA, Rohnert Park, USA) and filtered with a fourth-order zero-lag Butterworth low-pass filter at a cut-off frequency of 12 Hz to eliminate higher-frequency noise. Foot contact was defined as vertical GRF > 50 N. If participants stepped on two force platforms, the force, free moment, and centre of pressure (CoP) were re-calculated as one force platform using the force platforms' six-force component data [10]. We confirmed the validity of this method before starting the current study. Here, our participants stepped on two force platforms in one-fifth of all valid trials.

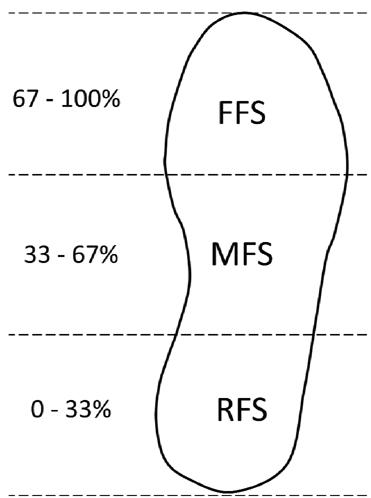

Fig. 4. The results for the lower limb joint angle [°, mean ± SD] and joint torque [Nm, mean ± SD]. Both joint angle and torque were standardised from 0 to 100% during the stance phase and were averaged for all subjects under each shoe condition (black line: minimalist shoes, black dashed line: traditional shoes, and grey line: maximalist shoes)

The foot strike pattern was determined using a foot--strike index [7]. The foot strike index was defined as the distance from the heel to the CoP at foot contact as a percentage of the foot length (from heel to toe markers); the CoP at foot contact is located on the front one-third of the shoe (i.e., the foot-strike index is from 67% to 100%): forefoot strike, on the middle third of the shoe (from 33% to 63%); and midfoot strike and rearfoot strike: on the rear one-third of the shoes (from 0% to 33%) (Fig. 4).

Additionally, we calculated the contact time and mass displacement centre (the height difference between foot contact and its bottom) as gait parameters. However, we could not calculate the aerial time, step length and step frequency because we could not measure both steps before and after the step that struck the force plates owing to laboratory constraints.

A 15-segment full-body model was constructed to calculate mass centre. The upper half of body segments was used only to obtain the centre of mass. The hip joint centre was estimated as 30% distal, 14% medial and 22% posterior from the anterior superior iliac spine [2]. The knee joint's centre was defined as the midpoint between the medial and lateral epicondyles, whereas the ankle joint's centre was defined as the midpoint between the medial and lateral malleoli. The local coordinate system was set up as the right-hand system; the x-axis was directed laterally, the y-axis was directed anteriorly and the z-axis was directed superiorly. The lower extremity joint angles (knee and ankle) were calculated as the angles of the distal segment concerning the proximal segment using the XYZ Cardan rotation sequence (X, flexion/extension; Y, abduction/adduction; Z, internal/external rotation). Lower extremity joint torques were calculated using the Newton–Euler inverse dynamics method. We only evaluated the sagittal plane (x-axis) joint angle and torque, which were defined using signs as follows: ankle plantarflexion (–)/dorsiflexion (+), knee flexion (–)/extension (+). Lower extremity joint power was calculated using the dot product of the joint torque and joint angular velocity. Stance phase lower extremity negative and positive joint works were calculated by integrating the negative and positive joint power. All calculations were performed using MATLAB R2022a (MathWorks, Natick, MA, USA).

2.11. Statistical analysis

All variables were averaged over five trials in each shoe condition for each participant for statistical analysis. First, we considered the distribution normality with the Shapiro–Wilk test. However, some variables were not normally distributed. Thus, we employed the Friedman test for statistical analysis in all variables to examine the effect of different footwear types (i.e., MIN, TRAD and MAX shoes) ($\alpha = 0.05$). The same statistical analysis was used for the foot strike index. If significant main effects of footwear were found, the post-hoc pairwise test with Holm correction was used ($\alpha = 0.05$). All statistical analyses were conducted using IBM SPSS software (The R Foundation for Statistical Computing, Vienna, Austria, https://www.r-project.org/SPSS Version 28.0.1.1(14), Chicago, IL, USA).

3. Results

No significant main effect of footwear on the foot strike index was observed ($F_{2,30} = 3.374$, $p = 0.055$, $p\eta^2 = 0.252$). The foot strike pattern and foot strike index for each participant under each condition is listed in Table 1.

All the results of Friedman test and post hoc analysis are summarized in Table 2. An example of one participant's ankle and knee joint angle and torque normalised from 0% to 100% during the stance phase is presented in Fig. 5 and the ankle and knee joint negative and positive work during the stance phase for all participants are depicted in Fig. 6.

Table 1. Foot strike pattern* (mean foot strike index) for each participant

Subject no.	MIN	TRAD	MAX
1	FFS (84.7%)	FFS (89.9%)	FFS (83.9%)
2	FFS (73.8%)	FFS (68.4%)	MFS (65.5%)
3	FFS (72.9%)	FFS (70.4%)	FFS (74.1%)
4	FFS (72.3%)	FFS (70.3%)	FFS (73.3%)
5	FFS (73.9%)	FFS (75.5%)	FFS (72.7%)
6	FFS (77.1%)	FFS (79.6%)	FFS (72.7%)
7	MFS (64.7%)	FFS (69.1%)	MFS (59.8%)
8	FFS (83.8%)	FFS (74.9%)	MFS (65.1%)
9	FFS (72.8%)	MFS (65.4%)	MFS (50.9%)
10	MFS (55.5%)	MFS (48.7%)	MFS (53.5%)
11	MFS (66.3%)	MFS (66.9%)	MFS (63.4%)

* The foot strike pattern was decided by averaging the foot strike index for each shoe. The foot strike index was given as the distance from the heel to the CoP as a percentage of the foot length.

FFS – forefoot strike, MAX – maximalist, MFS – midfoot strike, MIN – minimalist, TRAD – traditional.

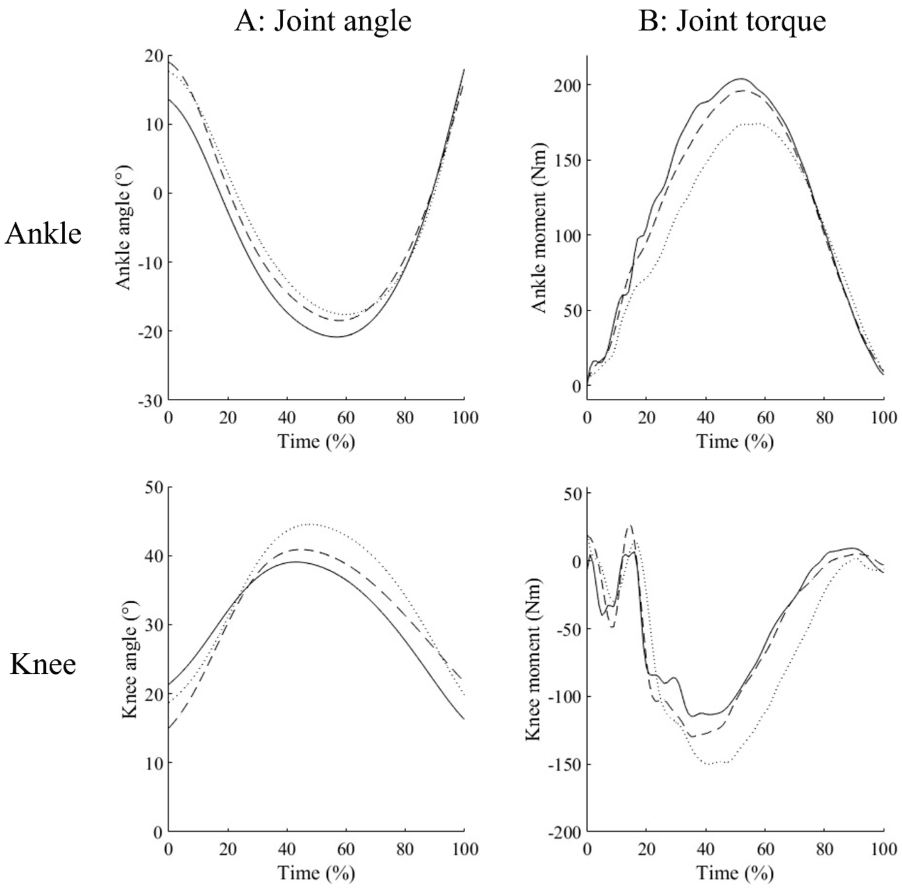

Fig. 5. The results of lower limb joints' negative work (J, mean ± SD)

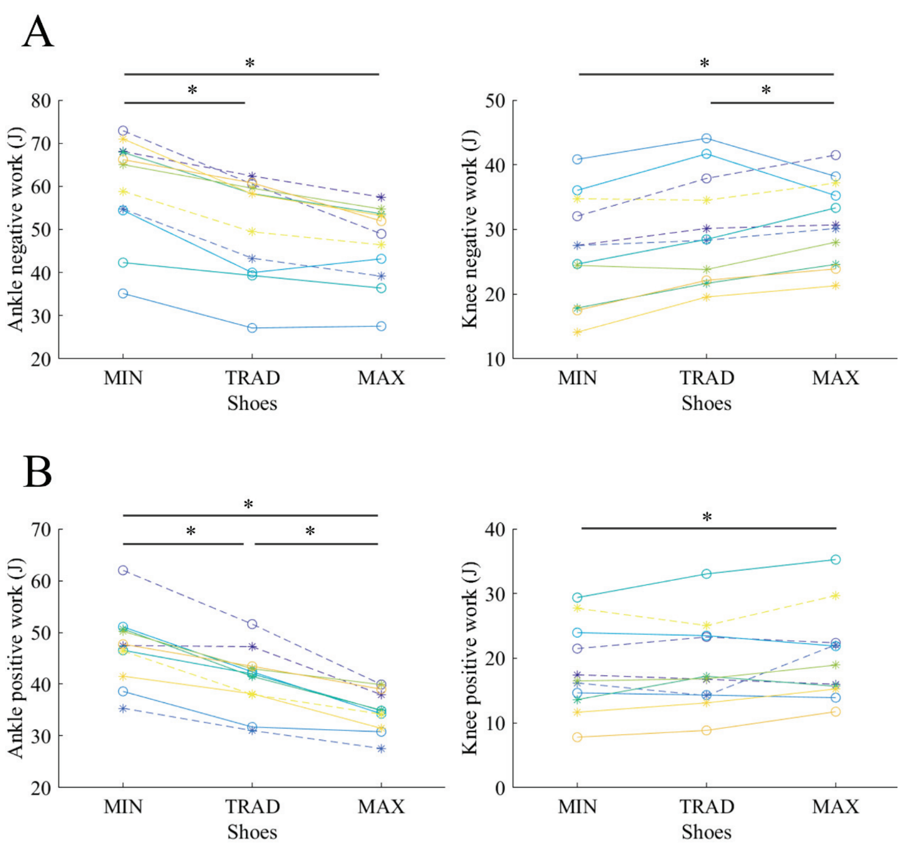

Fig. 6. The results of lower limb joints' positive work [J, mean ± SD]

3.1. Joint kinematics and kinetics

Ankle joint

There were significant main effects of footwear on the peak angle and peak plantarflexion torque. There was no significant difference in ankle angle at foot contact. Post-hoc analysis revealed that the ankle peak angle was significantly more dorsiflexed in the following order: MIN, TRAD and MAX shoes. The ankle peak plantarflexion torque was also significantly greater in the same order.

Knee joint

There were significant main effects of footwear on the knee joint peak flexion angle and peak extension torque. However, no significant main effect of footwear on the knee joint angle at foot contact was detected. Post-hoc analysis showed that the knee joint peak angle was significantly more flexed in MAX than in MIN. The knee peak extension torque was significantly lower in the following order: MIN, TRAD and MAX shoes.

3.2. Joint energetics

Ankle joint

There was a significant main effect of footwear on the ankle joint negative work and positive work. Post-hoc analysis revealed that the ankle joint negative work was significantly higher in MIN than in TRAD and MAX shoes. Additionally, the ankle joint positive work was significantly higher in the following order: MIN, TRAD and MAX shoes.

Knee joint

There was a significant main effect of footwear on the knee joint negative work ($F_{2,30} = 18.727$, $p < 0.001$) and positive work ($F_{2,30} = 7.818$, $p = 0.020$). Post-hoc analysis showed that the knee joint negative work was higher in MAX than in MIN and TRAD shoes (MIN = TRAD: $p = 0.136$; MIN < MAX: $p < 0.001$; TRAD < MAX: $p = 0.011$). The knee joint positive work was lower in MIN shoes than in MAX shoes (MIN = TRAD: $p = 0.176$; MIN < MAX: $p = 0.017$; TRAD = MAX: $p = 0.859$).

3.3. Gait parameter

There was a significant main effect of footwear on the contact time. By contrast, no significant main effect of footwear on the centre of mass displacement was observed. Post-hoc analysis revealed that the contact time was significantly longer in MAX than in TRAD shoes.

4. Discussion

The current study aimed to investigate midsole thickness' effects on non-rearfoot strikers' joint shock absorption and generation systems. Our results indicated that MAX shoes induced greater knee joint negative and positive work as well as lower ankle joint negative and positive work in non-rearfoot strikers. On the other hand, MIN shoes induced greater ankle joint negative and positive work as well as lower knee joint negative and positive work. These results support our hypothesis, therefore, thicker midsole shoes enable non-rearfoot runners to absorb the shock of landing and generate propulsive energy more at the knee joint than at the ankle joint, whereas thinner midsole shoes enable non-rearfoot runners to absorb such shock and generate such energy more at the ankle joint than at the knee joint.

The redistribution of joint negative and positive work from the knee to the ankle when using MIN shoes and from the ankle to the knee when using MAX shoes is consistent with the findings of previous studies investigating the effects of MIN [4], [12] or MAX shoes [4], [30] in rearfoot strike runners. Sobhani et al. [30] reported that the factors contributing to the greater ankle joint negative work in MIN shoes include not only the effect of reduced cushioning properties but also the effect of changing foot strike patterns (rearfoot to midfoot strikes). Although there were changes between midfoot and forefoot strikes in four participants in the current study, all of our participants did not shift to rearfoot strikes and there was no significant difference in strike index. Therefore, the effect of midsole thickness seems to be similar for both rearfoot and non-rearfoot strikers, and redistributing the ankle and knee joint negative and positive work is the pure effect of midsole thickness.

Thus, MIN and MAX shoes seem to play different roles in adjusting the load on knee and ankle joints. Non-rearfoot strikers have greater ankle joint negative work [14], [33] and load on the triceps surae and Achilles tendon [28], [33], [34]. Hence, it might be helpful for non-rearfoot strikers to reduce their shank muscle-tendon unit because MAX shoes could decrease the ankle's peak dorsiflexion angle and negative work. On the other hand, knee joint negative work increased in MAX shoes, in which the knee joint is the most common site of lower limb running-related injuries [35]. Although the load on the knee joint is higher, thicker shoes may be useful for non-rearfoot strikers to reduce ankle joint load because forefoot strikers have a lower risk of knee joint injuries than rearfoot strikers [8]. As for the MIN shoes, they seem to be beneficial for rearfoot strikers to reduce the impact of landing by shifting their strike patterns to more mid/forefoot strikes [23], [27]. However, for non-rearfoot strikers, and if rearfoot strikers do not shift their strike pattern, MIN shoes may not protect from landing impact [16].

As for the effect on running performance, MAX shoes decreasing ankle joint negative and positive work might also be useful although it is disadvantageous for running economy that a thicker midsole typically increases shoe mass [29]. Our results showed that the redistribution of ankle and knee joint positive work is similar to the joint negative work. The ankle joint is the largest energy absorber and generator joint in running [32] so that the decrease in negative and negative and positive ankle joint work in the same running task might lead to the improvement of the running economy. When forefoot strike runners had prolonged running, many of them shift their foot strike pattern toward midfoot or rearfoot strikes as the running distance increased [5], [21] due to the ankle plantar flexor muscle fatigue [17]. Thus, MAX shoes seem to be useful for prolonged running to keep runners' foot strike pattern because prolonged running redistributes the lower limb joint work from ankle to knee and hip joint resulting in worse running economy [26]. Nevertheless, a thicker midsole resulted in a worse running economy [24], [29] as shoe mass becomes heavier which deteriorates running economy by 1% per 100 g [9]. However, the development of state-of-the-art midsole material is lighter and more compliant, which increases midsole thickness without increasing shoe weight drastically [3], [6]. On the other hand, previous studies suggested that running with MIN shoes and barefoot could increase the storage and return of elastic energy at the Achilles tendon and result in an improvement of the running economy [9], [24]. The current study showed that MAX shoes lead to a greater plantar flexion angle at contact (Table 2), which could increase the length changes of the triceps surae muscle-tendon unit like forefoot strikers [34]. This may be an attempt to compensate for the decreased energy return of the Achilles tendon due to the plantar flexion restriction at the stance phase in MAX shoes.

As the previous studies reported that the joint flexion angle and extension torque has a linear relationship between the ankle and knee joint in the stance phase [13], [31], our results also showed the correlation between joint peak flexion angle and the peak extension torque, which led to the increase/de crease of negative and positive joint work. Throughout the stance phase, the ankle joint angle was more dorsiflexed and the knee joint angle was more extended in thinner midsole shoes (Fig. 4). The decreased ankle dorsiflexion angle, which results in a reduction in ankle joint shock absorption when using MAX shoes, might increase the demand for other shock absorption (i.e., knee joint flexion). In other words, the more dorsiflexed ankle angle when using MIN shoes might decrease the demand for knee joint shock absorption. The compensation of ankle and knee joint (dorsi)flexion might be attributable to the attempt of runners to maintain the oscillation of their whole-body centre of mass during the stance phase [11]. In the current study, our participants maintained their centre of mass displacement. Thus, ankle and knee joint flexion appears to compensate for the changes in each other, leading to the redistribution of joint work.

The current study had several limitations. First, although we selected MIN, TRAD and MAX shoes to examine the effect of midsole thickness, we could not control the shoe upper, outsole and heel-to-toe drop (i.e., the thickness difference between the forefoot and rearfoot region of the shoes). In particular, zero heel-to-toe drop had been reported to decrease the knee joint flexion angle and extension torque in rearfoot strikers [36]. Hence, our results regarding the knee joint when using MIN shoes were not only contributed by the thinner midsole thickness but also by the heel-to-toe drop. Second, rearfoot strikers were not investigated in this study; therefore, we could not directly compare the effect of midsole thickness between rearfoot and non-rearfoot strikers. Future studies examining the interaction effect between midsole thickness and foot strike patterns are necessary to be conducted. Third, in this study, our participants include both long--distance university athletes and recreational runners. Additionally, the thicknesses of the running shoes which participants usually wear were different, with some wearing shoes close to MAX and others close to TRAD. We could not examine the effects of running experience and different regular running shoes. Finally, due to laboratory constraints (the angle of view of the cameras and the size of the force platforms), we were

Table 2. Summary of all variables [median (interquartile range)]

	MIN	TRAD	MAX	Friedman test *P*-value	$\chi 2$	MIN vs. TRAD *P*-value	MIN vs. MAX *P*-value	TRAD vs. MAX *P*-value
Ankle								
angle at foot contact [°]	–12.08 (–17.59 ~ –7.93)	–9.39 (–16.84 ~ –6.73)	–15.67 (–21.40 ~ –7.96)	0.078	5.091	–	–	–
peak angle [°]*	23.00 (21.54 ~ 26.10)[c]	21.46 (19.13 ~ 23.33)	19.13 (15.95 ~ 22.41)[b]	< 0.001	18.180	0.033	< 0.001	0.033
peak torque [Nm]*	–201.54 (–209.78 ~ –184.97)[c]	–192.12 (–199.17 ~ –182.48)[b]	–174.62 (–182.09 ~ –168.17)[a,b]	< 0.001	20.182	0.055	< 0.001	0.021
negative work [J]*	65.05 (55.37 ~ 67.98)[b,c]	58.20 (45.20 ~ 60.03)[a]	48.96 (39.28 ~ 53.42)[a]	< 0.001	20.182	0.021	< 0.001	0.055
positive work [J]*	46.55 (43.03 ~ 48.96)[b,c]	41.48 (38.07 ~ 43.21)[a,c]	34.87 (32.77 ~ 38.49)[a,b]	< 0.001	22.000	0.038	< 0.001	0.038
Knee								
angle at foot contact [°]	–14.42 (–15.99 ~ –12.56)	–15.11 (–17.34 ~ –12.85)	–14.89 (–16.04 ~ –10.48)	0.307	2.364	–	–	–
peak angle [°]*	–37.88 (–38.72 ~ –33.72)[c]	–38.59 (–40.01 ~ –35.82)	–40.78 (–42.52 ~ –36.27)[a]	< 0.001	14.727	0.110	< 0.001	0.110
peak torque [Nm]*	140.18 (117.10 ~ 156.40)[b,c]	148.52 (133.96 ~ 161.74)[a,b]	154.89 (138.96 ~ 166.84)[a,b]	< 0.001	22.000	0.038	< 0.001	0.038
negative work [J]*	24.43 (17.66 ~ 27.52)[c]	24.84 (22.85 ~ 27.52)[c]	28.02 (24.41 ~ 32.02)[a,b]	< 0.001	18.727	0.136	< 0.001	0.011
positive work [J]*	16.17 (12.24 ~ 19.47)[c]	16.83 (13.86 ~ 20.26)	18.94 (15.46 ~ 22.23)[a]	0.004	7.818	0.176	0.017	0.859
Gait parameter								
contact time [ms]*	179.17 (168.33 ~ 195.00)	174.17 (168.75 ~ 188.33)[c]	180.08 (172.92 ~ 197.50)[b]	0.020	7.850	0.241	0.271	0.015
CoM displacement [mm]	50.63 (47.24 ~ 59.16)	48.95 (47.05 ~ 59.54)	58.29 (49.50 ~ 58.29)	0.761	0.545	–	–	–

* Indicates significance in Friedman test, [a] – significant deference than MIN shoes, [b] – significant deference than TRAD shoes, [c] – significant deference than MAX shoes.

The joint angle and torque sign were defined as follows: ankle plantarflexion (–) / dorsiflexion (+), knee flexion (–) / extension (+). Joint work is expressed as an absolute value and shown as positive.

not able to measure left-leg kinematics and ground reaction forces. Kong et al. [20] reported that most of the kinematic differences between the dominant and non-dominant leg were remarkable but small and within the normal intra-subject variability; therefore, we think it is valid to evaluate only the right leg.

5. Conclusion

We investigated the effects of midsole thickness on non-rearfoot strikers with the use of MIN, TRAD and MAX shoes. Our results indicated that non-rearfoot strikers' joint negative and positive work was redistributed from the knee to the ankle when using MIN shoes or from the ankle to the knee when using MAX shoes. In this study, we were not able to examine the direct effect of midsole thickness on running-related injuries. Therefore, it is recommended that future research employs more rigorous study designs, such as randomised controlled trials and longitudinal studies, to provide a more accurate assessment of the effect of these shoes on lower limb injury.

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Conflict of interest

There is no conflict of interest to declare.

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