Joel T. Fuller, Dominic Thewlis, Margarita D. Tsiros, Nicholas A.T. Brown, Jonathan D. Buckley

Six-week transition to minimalist shoes improves running economy and time-trial performance

Journal of Science and Medicine in Sport, 2017; 20(12):1117-1122

Final publication at http://dx.doi.org/10.1016/j.jsams.2017.04.013

G Model
JSAMS-1511; No. of Pages 6
ARTICLE IN PRESS
Journal of Science and Medicine in Sport xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Journal of Science and Medicine in Sport
journal homepage: www.elsevier.com/locate/jsams

Original research

Six-week transition to minimalist shoes improves running economy and time-trial performance

Joel T. Fuller[a,b,*], Dominic Thewlis[a], Margarita D. Tsiros[a], Nicholas A.T. Brown[c], Jonathan D. Buckley[a]

[a] Alliance for Research in Exercise, Nutrition and Activity (ARENA), Sansom Institute for Health Research, University of South Australia, Australia
[b] Faculty of Medicine and Health Sciences, Macquarie University, Australia
[c] Australian Institute of Sport, Australia

ARTICLE INFO

Article history:
Received 17 September 2016
Received in revised form 8 April 2017
Accepted 16 April 2017
Available online xxx

Keywords:
Athletes
Footwear
Indirect calorimetry
Muscle strength
Gait
Footfall pattern

ABSTRACT

Objectives: This study investigated if gradually introducing runners to minimalist shoes during training improved running economy and time-trial performance compared to training in conventional shoes. Changes in stride rate, stride length, footfall pattern and ankle plantar-flexor strength were also investigated.
Design: Randomised parallel intervention trial.
Methods: 61 trained runners gradually increased the amount of running performed in either minimalist (n = 31) or conventional (n = 30) shoes during a six-week standardised training program. 5-km time-trial performance, running economy, ankle plantar-flexor strength, footfall pattern, stride rate and length were assessed in the allocated shoes at baseline and after training. Footfall pattern was determined from the time differential between rearfoot and forefoot (TD_{R-F}) pressure sensors.
Results: The minimalist shoe group improved time-trial performance (effect size (ES): 0.24; 95% confidence interval (CI): 0.01, 0.48; $p = 0.046$) and running economy (ES 0.48; 95%CI: 0.22, 0.74; $p < 0.001$) more than the conventional shoe group. There were no minimalist shoe training effects on ankle plantar-flexor concentric (ES: 0.11; 95%CI: −0.18, 0.41; $p = 0.45$), isometric (ES: 0.23; 95%CI: −0.17, 0.64; $p = 0.25$), or eccentric strength (ES: 0.24; 95%CI: −0.17, 0.65; $p = 0.24$). Minimalist shoes caused large reductions in TD_{R-F} (ES: 1.03; 95%CI: 0.65, 1.40; $p < 0.001$) but only two runners changed to a forefoot footfall. Minimalist shoes had no effect on stride rate (ES: 0.04; 95%CI: −0.08, 0.16; $p = 0.53$) or length (ES: 0.06; 95%CI: −0.06, 0.18; $p = 0.35$).
Conclusions: Gradually introducing minimalist shoes over a six-week training block is an effective method for improving running economy and performance in trained runners.

1. Introduction

Choice of running shoe is important for distance runners because shoes can affect running performance.[1] Some studies have suggested that wearing minimalist shoes (or racing flats) during running competition should be advantageous for running economy[1] and performance,[2] and runners have been doing this for many years.[3,4] However, a recent systematic review identified no studies investigating the effect of training in minimalist shoes on running performance.[1]

Running economy is an indirect measure of running performance and has been investigated in runners training with minimalist shoes.[5–7] A prospective cohort study demonstrated that runners improved running economy by 8% following a 4-week prescribed program for training in minimalist shoes.[7] However, subsequent controlled trials found that training in minimalist shoes did not improve running economy when (1) runners followed a flexible minimalist shoe training prescription that allowed them to increase minimalist shoe mileage from week 4–10 as they felt was appropriate[5] or (2) prescribed use of minimalist shoes was combined with instructions to use a forefoot footfall pattern and increase stride rate.[6] Small sample sizes ($n \leq 25$) and different instructions provided to runners may explain the variable findings across studies. Additionally, no studies have standardised training when comparing running economy between minimalist and con-

* Corresponding author.
E-mail address: joel.fuller@mq.edu.au (J.T. Fuller).

http://dx.doi.org/10.1016/j.jsams.2017.04.013
1440-2440/

Please cite this article in press as: Fuller JT, et al. Six-week transition to minimalist shoes improves running economy and time-trial performance. *J Sci Med Sport* (2017), http://dx.doi.org/10.1016/j.jsams.2017.04.013

trol shoes, and no studies have included direct measures of running performance such as time-trial testing.

Running in minimalist shoes can increase the tendency to make initial ground contact with the midfoot or forefoot instead of the rearfoot[7–9] resulting in increased stride rate[7,10,11] and plantar-flexion moments at the ankle.[8] Several researchers have anticipated that these changes will result in a more efficient running gait.[7,12] However, changing from a rearfoot to forefoot footfall pattern has shown to result in similar or poorer running economy.[13] Additionally, runners find it difficult to maintain a forefoot footfall pattern throughout a prolonged run due to fatigue of the ankle plantar-flexor muscles.[14] As a result, the importance of a forefoot footfall pattern for improving running performance in minimalist shoes remains unclear.

This study investigated if using minimalist shoes improved time-trial performance and running economy compared to conventional shoes during a standardised six-week training program. Footfall pattern, stride rate and length, and ankle plantar-flexor strength were also investigated. It was hypothesised that (1) runners in minimalist shoes would use a forefoot footfall, reduce stride length, and increase stride rate and ankle plantar-flexor strength, and (2) this minimalist shoe intervention would contribute to greater improvements in time-trial performance and running economy.

2. Methods

Sixty-one male distance runners were recruited. Ethical approval was obtained from the University of South Australia Human Research Ethics Committee and the study was registered with the Australian New Zealand Clinical Trials Registry (ACTRN12613000642785). The study protocol has been previously published.[15] Runners provided written informed consent prior to enrolment. Sample size was sufficient to detect a Cohen's *d* effect size of 0.30 with 80% power and 5% significance level using analysis of covariance.[15,16]

Eligible participants were 18–40 years old, ran at least 15-km/week, could run 5-km in <23 min, used conventional shoes, had no previous minimalist shoe experience and were habitual rearfoot footfall runners. Footfall pattern eligibility was assessed during five over-ground running trials at preferred running speed in the runners own shoes using a high-speed digital camera filming at 200 Hz. Only runners that landed heel first in all trials were eligible. Runners were excluded if they used orthotics, had a current or recent musculoskeletal injury (<3 months) or history of surgery in the previous year.

A randomised parallel intervention trial design was used (Fig. 1). Participants attended a familiarisation session 1-week before baseline testing to practice all experimental procedures using their usual running shoes and minimise potential learning effects. Time-trial performance during this familiarisation session was used to randomise participants to shoe group via a process of minimisation.[15,17] One-week after this practice session, participants completed baseline assessments in their allocated shoes (conventional or minimalist). Outcomes assessed (in order of assessment) were running economy and kinematics, time-trial performance and ankle plantar-flexor strength. All outcome measures were re-assessed in the allocated shoes after six weeks of standardised training, at the same time of day. Participants did not complete training on the day of testing and fasted from food (water permitted) for 3-h before testing.

Participants were randomly allocated to conventional (Asics Gel Cumulus; mass: 333 ± 25 g per shoe; heel stack height: 32 mm; heel drop: 9 mm) or minimalist shoes (Asics Piranha SP4; mass: 138 ± 10 g per shoe; heel stack height: 22 mm; heel drop: 5 mm). The Asics Piranha scored 72% on the minimalist index for classifying shoes on a scale from least (0%) to most (100%) minimalist.[18] The Asics Piranha has been shown to cause running kinematic changes that are typical of minimalist shoes.[11]

Body mass was assessed before each assessment of running economy. Participants then completed a 5-min warm-up on a motorised treadmill (Model 645, Quinton Instrument Co., WA, USA) set to a comfortable jogging speed of 8 $km\,h^{-1}$. Running economy was then assessed for 6 min at 11, 13 and 15 $km\,h^{-1}$ in a fixed order separated by 4-min rest breaks. Expired gases were collected (Hans–Rudolph two-way non-return breathing valve) and passed through an indirect calorimetry system (TrueOne 2400, ParvoMedics, UT, USA) to determine oxygen uptake. Running economy was the rate of oxygen uptake ($l\,min^{-1}$) during the final minute of running at each speed. All participants achieved steady state oxygen uptake with respiratory exchange ratio (RER) below 1.00 at 11 and 13 $km\,h^{-1}$, but only half achieved steady state oxygen uptake with RER <1.00 at 15 $km\,h^{-1}$. As a result, these latter data were excluded.[19] Reliability was excellent for each speed (coefficient of variation [CV] <2.0%).[2]

One force sensitive resistor was placed under the heel (rearfoot sensor) and metatarsal heads (forefoot sensor) to identify footfall pattern, and calculate stride rate and length during running economy assessment. Sensors were placed on the midline of the shoe (online Supplement 1). Pressure data were collected from the sensors using a wireless Delsys Trigno system (Delsys Inc., MA, USA) sampling at 2000 Hz. Footfall pattern was determined from the time differential between rearfoot and forefoot (TD_{R-F}) sensors. A forefoot footfall occurred if the forefoot sensor contacted the ground before the rearfoot sensor (i.e. negative TD_{R-F}). Stride rate was the number of right foot contacts per minute. Average stride length was calculated as the product of treadmill speed and average time taken to complete each stride.[20] All computations were performed in MATLAB (R2013a, MathWorks, MA, USA). Reliability was excellent for each speed (CV <2.2%).[2]

Running performance was assessed using a 5-km time-trial on a motorised treadmill set at 0% grade. We did not increase treadmill incline to account for reduced air resistance because this would have effected running kinematics. Participants selected their starting speed and adjusted the treadmill speed throughout the time-trial to finish in the fastest possible time. Starting speed remained constant across testing sessions. Participants were blinded to running time and speed but not distance. Reliability was excellent (CV = 1.3%).[2]

Ankle plantar-flexor strength was assessed using an isokinetic dynamometer (Biodex System 4, Biodex Medical Systems, NY, USA) with participants in a reclined seated position and the knee joint in 20–30° flexion. Peak isometric torque (PIT) was measured with the ankle joint in the anatomical neutral position and defined as the peak torque achieved during the best of two five-second efforts. Peak concentric (PCT) and eccentric torque (PET) were measured at an angular velocity of $30^{\circ}\,s^{-1}$ between full ankle joint plantar-flexion and the anatomical neutral position. The peak torque achieved across two sets of three concentric and eccentric repetitions was considered PCT and PET, respectively. Test–retest assessment of 10 runners indicated moderate reliability (PIT: CV 7.5%; PCT: CV 7.8%; PET: CV 6.5%).

All participants completed a 6-week progressive training program (online Supplement 2) that was adapted from a program[21] known to improve performance in trained runners. Training duration and relative intensity were standardised across participants.[15] Training intensity was prescribed relative to peak heart rate (HR_{Peak}) achieved during baseline 5-km time-trial assessment. Training involved two interval running sessions at 85–90% HR_{Peak} and two continuous running sessions at 65–80% HR_{Peak} each week. The duration of interval training was increased throughout the

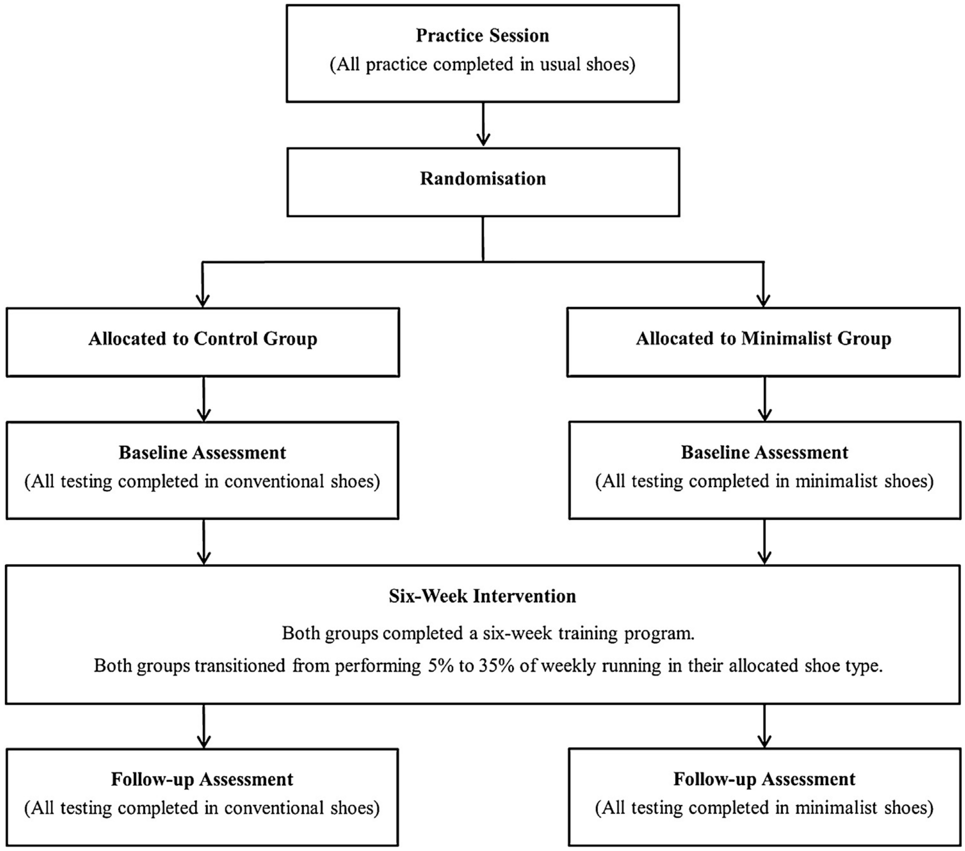

Fig. 1. Study protocol.

program so that a greater percentage of training was completed at high intensity (85–90% HR_{Peak}). Participants monitored training intensity using heart rate monitors (Polar F1, Polar Electro Oy, Kempele, Finland). Compliance with training was calculated by dividing the total duration of training performed at the prescribed intensity by the total duration of prescribed training. Participants were instructed not to perform any additional training.

Runners in each group gradually increased the amount of running in their allocated shoes and decreased the amount of running in their usual running shoes (online Supplement 2). Participants completed ~5% of weekly running in their allocated shoes during Week 1 and this increased to ~35% of weekly running in Week 6. Increasing minimalist shoe use to 35% of weekly running was chosen as a safe and realistic target for participants to achieve during the 6-week intervention. Participants completed a total of 3.5 h (40–50 km) of running in their allocated shoes during the intervention. Compliance was calculated by dividing the total duration of training performed in allocated shoes (from training diaries) by the total duration of prescribed allocated shoe use.

Statistical analysis was performed using SPSS (v21, IBM, NY, USA). Effects of the allocated shoes on time-trial performance and ankle plantar-flexor strength were compared using analysis of covariance to adjust for baseline data. Running economy, TD_{R-F}, stride rate and length were assessed with linear fixed-effects models using the MIXED procedure in SPSS. Fixed effects in the model were shoe, speed, time and shoe*speed*time interaction. Speed and time were treated as repeated observations. Body mass was included as a covariate in the running economy model to account for any changes to participant mass. Shoe mass was an additional covariate.

Statistical significance was set at $\alpha = 0.05$. Effect sizes (ES) and 95% confidence intervals (95%CI) were quantified using standardised mean differences and considered small (0.20–0.49), moderate (0.50–0.79) and large (≥0.80).[22] Effect sizes <0.20 were considered trivial.[22] Quantile–quantile normality and residual plots were used to assess normality of data and normality, homoscedasticity and independence of residuals.

3. Results

A total of 230 runners were assessed for eligibility and 61 (age: 27 ± 7 years; body mass: 74.6 ± 9.3 kg; weekly distance: 25 ± 14 km) were enrolled in the study (Fig. 2). The conventional and minimalist shoe groups were balanced for 5-km time-trial performance when using their usual running shoes during the familiarisation session (1278 ± 67 and 1283 ± 80 s, respectively).

Fifty runners completed the training program and follow-up assessment (Fig. 2). Compliance with training was 94.0 ± 8.1% (range 69.4–100.0%), with no difference between groups ($p = 0.75$). Compliance with the transition to allocated shoes was 94.2 ± 8.0% (range 67.8–100.0%), with no difference between groups ($p = 0.55$).

There was no difference in time-trial performance between shoe groups at baseline ($p = 0.64$; Table 1). Training improved time-trial performance in the minimalist shoe group ($p < 0.001$) and the conventional shoe group ($p = 0.002$) (Table 1). The improvement in performance was greater in the minimalist shoe group ($p = 0.046$), although the magnitude of difference was small (Table 1).

There was a shoe*speed*time interaction for running economy ($p = 0.01$). Training in minimalist shoes was accompanied by small improvements in running economy at 11 km h^{-1} ($p = 0.003$) and moderate improvements at 13 km h^{-1} ($p < 0.001$) (Table 1). These improvements were greater than changes in the conventional shoe group at 13 km h^{-1} ($p = 0.01$) but not 11 km h^{-1} ($p = 0.10$) (Table 1). Including shoe mass did not improve model fit ($p = 0.18$) and did

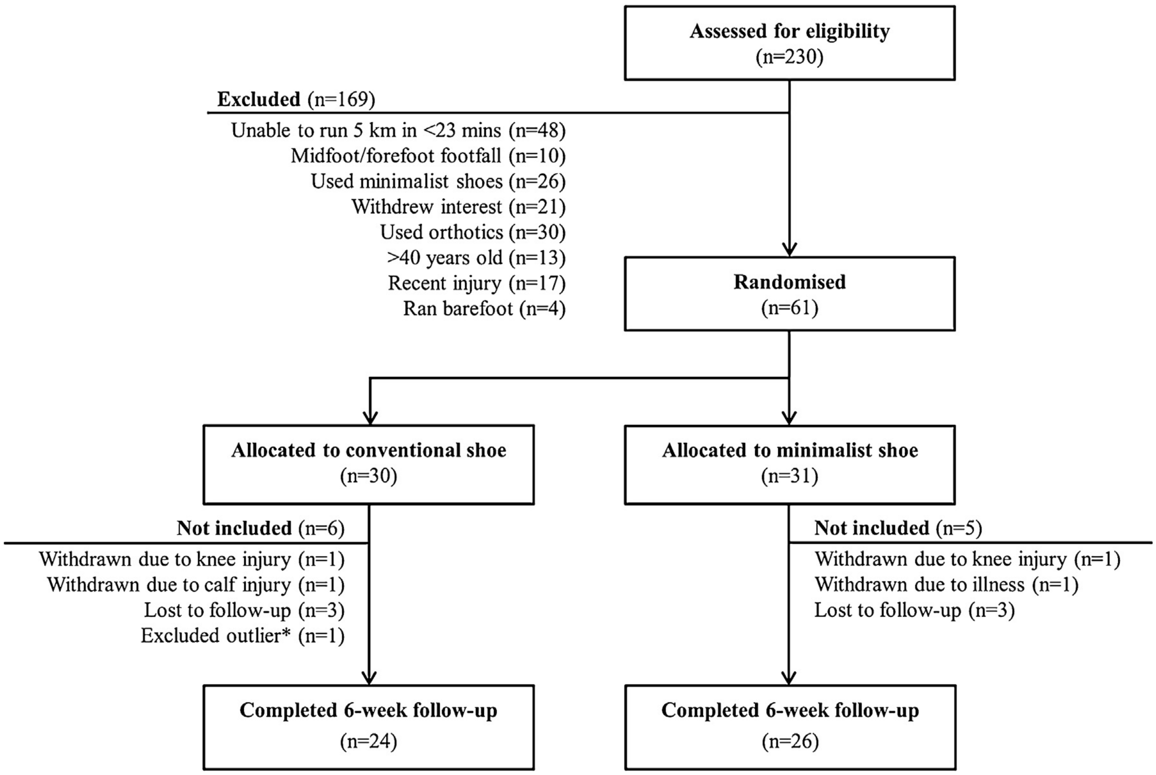

Fig. 2. Participant flow chart. *Participant excluded as an outlier after running 5-km time-trial 114 s slower at completion of the six-week training program.

not explain the shoe*speed*time interaction (online Supplement 3).

There were no shoe*speed*time interactions for TD_{R-F} ($p = 0.99$), stride rate ($p = 0.99$) or length ($p = 0.98$). There was a main effect of shoe type on TD_{R-F} ($p < 0.001$). Minimalist shoes caused a large reduction in TD_{R-F} (ES: 1.03; 95%CI: 0.65, 1.40; $p < 0.001$) but only two runners used a forefoot footfall (Table 1). There were no main effects of shoe type for stride rate ($p = 0.97$) or length ($p = 0.96$).

Training in minimalist shoes had no effect on PIT ($p = 0.25$), PCT ($p = 0.45$) or PET ($p = 0.24$) when compared to training in conventional shoes (Table 1).

4. Discussion

This study demonstrated that training in minimalist shoes caused small improvements in time-trial performance and moderate improvements in running economy compared with training in conventional shoes. Contrary to our hypothesis, improvements in running performance and economy were not accompanied by changes in ankle plantar-flexor strength, stride rate or length, and only two runners used a forefoot footfall.

This study is the first to longitudinally investigate the effect of training in minimalist shoes on time-trial performance. Longitudinal research is important because it better informs runners about the effects of different shoes on running performance than acute studies, which only investigate the effect of shoes during a single session. Time-trial measurements are desirable because they can be more easily related to race performance than sub-maximal tests of running economy.[1]

The minimalist shoe group improved time-trial performance by an additional 21.1 s (95%CI: 0.4, 41.8 s) when compared to the conventional shoe group. This was considered a small ES in our cohort because time-trial time was highly variable (pooled SD: 87.0 s). Elite runners are likely to have more consistent time-trial times. Therefore, if the 21.1 s improvement was repeated in a cohort of elite runners it could represent a much larger and more meaningful ES.[23]

The greater improvements in running economy and performance for the minimalist shoe group were accompanied by large reductions in TD_{R-F}, despite only two runners changing to a forefoot footfall. This suggests that most runners in the minimalist shoe group changed to a less-pronounced rearfoot footfall rather than switching footfall pattern entirely. The method used to assess TD_{R-F} did not account for frontal plane motion of the foot so these results should be interpreted with caution. However, we speculate that subtle changes to foot landing position when training in minimalist shoes might be sufficient to improve running economy and performance. Indeed, a recent study demonstrated increased energy absorption and generation at the ankle joint in runners who made subtle changes to foot landing position (contact angle changed from 7.4° to 2.4° dorsi-flexion) when running in minimalist shoes.[11] Similarly, another study demonstrated increased intrinsic foot muscle cross-sectional area in runners who changed contact angle from 8.6° to 2.7° dorsiflexion during 12 weeks of minimalist shoe training.[24] Increased energy absorption and generation at the ankle joint and increased intrinsic foot muscle strength have been proposed as mechanisms for improving elastic-energy storage and recovery in the Achilles' tendon[11] and arch of the foot.[12] Future studies should use more precise methods of assessing the contribution of subtle footfall pattern changes to running economy and performance in minimalist shoes.

The 3% improvement in running economy in our study was smaller than previously observed 8% improvements in a cohort of runners who increased stride rate and included more runners who changed to a forefoot footfall when training in minimalist shoes.[7] The minimalist shoes used by that cohort had a lower heel stack height and heel-to-toe drop than the minimalist shoes in our study. These differences might explain why only two runners in our cohort changed to a forefoot footfall and no effects on stride rate and length were observed. Nonetheless, previous studies have not reported

Table 1
Body mass, time-trial, running economy, ankle plantar-flexor strength, footfall pattern, time differential between rearfoot and forefoot pressure sensors, stride rate and stride length for minimalist and conventional shoe groups.

Outcome	Conventional shoe group (n = 24)			Minimalist shoe group (n = 26)			Minimalist shoes ES vs. conventional shoes ES (95%CI)
	Baseline	Week 6	ES (95%CI)	Baseline	Week 6	ES (95%CI)	
Body mass (kg)	73.5 ± 9.5	73.7 ± 10.0	0.02 (−0.05, 0.08)	75.8 ± 9.4	76.1 ± 9.0	0.04 (−0.03, 0.10)	0.02 (−0.07, 0.11)
Time-trial (s)	1269 ± 82	1245 ± 85[a]	0.29 (0.12, 0.47)	1258 ± 91	1213 ± 89[a,b,c]	0.50 (0.32, 0.67)	0.24 (0.01, 0.48)
Running economy ($l\,min^{-1}$)							
11 $km\,h^{-1}$	2.73 ± 0.18	2.72 ± 0.19	0.09 (−0.19, 0.37)	2.70 ± 0.18	2.62 ± 0.19[b]	0.42 (0.15, 0.69)	0.32 (−0.06, 0.71)
13 $km\,h^{-1}$	3.23 ± 0.20	3.24 ± 0.19	−0.01 (−0.29, 0.28)	3.23 ± 0.19	3.12 ± 0.19[a,b,c]	0.54 (0.26, 0.80)	0.55 (0.16, 0.94)
Peak torque (N m)							
Isometric	126 ± 32	123 ± 30	−0.10 (−0.38, 0.17)	126 ± 29	128 ± 21	0.18 (−0.17, 0.52)	0.23 (−0.17, 0.64)
Concentric	111 ± 24	112 ± 25	0.05 (−0.23, 0.32)	115 ± 25	119 ± 21	0.17 (−0.04, 0.38)	0.11 (−0.18, 0.41)
Eccentric	123 ± 28	122 ± 23	0.04 (−0.35, 0.42)	123 ± 28	128 ± 24	0.18 (−0.07, 0.44)	0.24 (−0.17, 0.65)
Stride rate (strides min^{-1})							
11 $km\,h^{-1}$	82 ± 4	82 ± 4	0.07 (−0.11, 0.26)	82 ± 4	82 ± 4	0.09 (−0.08, 0.27)	0.02 (−0.22, 0.26)
13 $km\,h^{-1}$	84 ± 5	85 ± 5	0.03 (−0.15, 0.22)	84 ± 5	85 ± 5	0.13 (−0.04, 0.31)	0.10 (−0.15, 0.36)
15 $km\,h^{-1}$	87 ± 5	87 ± 5	0.08 (−0.12, 0.27)	87 ± 5	88 ± 5	0.10 (−0.08, 0.29)	0.02 (−0.24, 0.29)
Stride length (cm)							
11 $km\,h^{-1}$	224 ± 12	223 ± 12	0.06 (−0.13, 0.24)	225 ± 12	223 ± 11	0.10 (−0.08, 0.28)	0.04 (−0.19, 0.28)
13 $km\,h^{-1}$	259 ± 15	259 ± 14	0.03 (−0.16, 0.21)	260 ± 15	258 ± 14	0.14 (−0.04, 0.32)	0.11 (−0.14, 0.37)
15 $km\,h^{-1}$	288 ± 17	287 ± 16	0.06 (−0.13, 0.26)	288 ± 17	286 ± 16	0.12 (−0.06, 0.30)	0.05 (−0.21, 0.32)
TD_{R-F} (ms)							
11 $km\,h^{-1}$	48.2 ± 14.5	46.5 ± 14.0	0.12 (−0.24, 0.48)	33.8 ± 14.5[a,c]	33.7 ± 14.0[a,c]	0.00 (−0.35, 0.35)	−0.12 (−0.60, 0.36)
13 $km\,h^{-1}$	44.7 ± 13.2	43.2 ± 11.5	0.12 (−0.24, 0.48)	30.2 ± 13.2[a,c]	29.7 ± 11.5[a,c]	0.04 (−0.32, 0.40)	−0.08 (−0.58, 0.42)
15 $km\,h^{-1}$	41.5 ± 13.6	38.7 ± 11.1	0.23 (−0.14, 0.60)	28.4 ± 13.6[a,c]	26.9 ± 11.1[a,c]	0.12 (−0.24, 0.48)	−0.11 (−0.63, 0.41)
Forefoot footfall (count)							
11 $km\,h^{-1}$	0/24	0/24	*	1/26	2/26	*	*
13 $km\,h^{-1}$	0/24	0/24	*	1/26	2/26	*	*
15 $km\,h^{-1}$	0/24	0/24	*	1/26	2/26	*	*

Data are presented as mean ± standard deviation. Effect sizes (ES) and 95% confidence intervals (CI) are presented so that positive values indicate beneficial outcomes of training or minimalist shoe use. TD_{R-F}, time differential between rearfoot and forefoot.
[a] Different to conventional shoe at baseline ($p < 0.05$).
[b] Different to minimalist shoe at baseline ($p < 0.05$).
[c] Different to conventional shoe at Week 6 ($p < 0.05$).
[*] Standardised mean difference not calculated because data is not continuous.

any relationships between stride rate, footfall pattern and running economy.[7] Thus, it remains unclear whether runners in our study would have achieved greater improvements in running economy if they had increased stride rate and used a forefoot footfall. Instead, the smaller improvement in our study could be due to the lower total exposure to minimalist shoes (3.5 h) compared to previous studies (5 h).[7]

Several different methods for transitioning to minimalist shoes have been described in the literature[7,25,26] but there is currently no clinical standard. Increased lower limb pain and injury risk has been reported for runners transitioning to more than 50% of weekly running in minimalist shoes over 12 weeks[26] and increased bone marrow edema has been reported in runners who do not follow a prescribed introduction to minimalist shoes during 10 weeks of running.[25] In the present study, runners transitioned to 35% of weekly running in minimalist shoe over 6 weeks so that the exposure was below levels previously associated with bone marrow edema,[25] pain and injury.[26] We did not instruct runners in the minimalist shoe group to perform foot, ankle, and calf strength and mobility exercises that have been used in other studies[6,7,27] because we wanted to isolate the effects of minimalist shoes.

This study had important limitations. First, only male runners were included to minimise heterogeneity of running performance, which limits the generalisability of the findings. Second, all testing was performed on a treadmill so the results might not be generalisable to over-ground running. Third, all training was performed over-ground so not all training effects may have translated to running kinematics, economy and performance testing, which was performed on a treadmill. Fourth, it was not possible to determine whether improved running economy and performance resulted from training or participants becoming better acclimatised to running in new shoes. Fifth, the minimalist shoe group did not complete additional assessments in conventional shoes so it is not possible to determine if the greater improvements in performance that resulted from training in minimalist shoes will translate to better performance in conventional shoes. Last, the protocol for assessing ankle plantar-flexor strength was associated with large test–retest error and might not have been able to detect meaningful improvements. More accurate protocols will be required to further investigate the effects of minimalist shoes on ankle plantar-flexor strength.

5. Conclusion

Gradual introduction of minimalist shoes during a 6-week training program improved time-trial performance and running economy more than conventional shoes. Minimalist shoes caused runners to use a less-pronounced rearfoot footfall, although only two runners changed to a forefoot footfall. Training in minimalist shoes did not effect ankle plantar-flexor strength, stride rate or length. Performing 5–35% of weekly running in minimalist shoes appears to be an effective practice for maximising improvements in running economy and performance that result from training.

Please cite this article in press as: Fuller JT, et al. Six-week transition to minimalist shoes improves running economy and time-trial performance. *J Sci Med Sport* (2017), http://dx.doi.org/10.1016/j.jsams.2017.04.013

Practical implications

- Gradually introducing runners to minimalist shoes over a six-week training block improved running economy and time-trial performance more than conventional shoes.
- Minimalist shoes caused runners to use a less-pronounced rear-foot footfall, although only two runners used a forefoot footfall.
- Minimalist shoes did not affect stride rate, stride length, or ankle plantar-flexor strength.

Acknowledgements

The authors would like to thank Dr Francois Fraysse for helping to write the MATLAB code, Jogger's World Adelaide store (SA, Australia) for providing the footwear for this research at reduced cost, and Asics Oceania for donating twenty pairs of Asics Gel-Cumulus to support this research. The lead author was the recipient of an Australian Postgraduate Award and a Vice Chancellor and President's Scholarship from the University of South Australia. This study received no other sources of financial support. No supporting organisation had any role in data collection, analysis and interpretation, or the right to approve or disapprove publication of this manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jsams.2017.04.013.

References

1. Fuller JT, Bellenger CR, Thewlis D et al. The effect of footwear on running performance and running economy in distance runners. *Sports Med* 2015; 45(3):411–422.
2. Fuller JT, Thewlis D, Tsiros MD et al. Effects of a minimalist shoe on running economy and 5 km running performance. *J Sports Sci* 2016; 34(18):1740–1745.
3. Altman AR, Davis IS. Barefoot running: biomechanics and implications for running injuries. *Curr Sports Med Rep* 2012; 11(5):244–250.
4. Rothschild CE. Primitive running: a survey analysis of runners' interest, participation, and implementation. *J Strength Cond Res* 2012; 26(8):2021–2026.
5. Ridge ST, Standifird T, Rivera J et al. The effect of training in minimalist running shoes on running economy. *J Sports Sci Med* 2015; 14(3):643–647.
6. Warne JP, Moran KA, Warrington GD. Eight weeks gait retraining in minimalist footwear has no effect on running economy. *Hum Mov Sci* 2015; 42:183–192.
7. Warne JP, Warrington GD. Four-week habituation to simulated barefoot running improves running economy when compared with shod running. *Scand J Med Sci Sports* 2014; 24(3):563–568.
8. Paquette MR, Zhang S, Baumgartner LD. Acute effects of barefoot, minimal shoes and running shoes on lower limb mechanics in rear and forefoot strike runners. *Footwear Sci* 2013; 5(1):9–18.
9. Fuller JT, Amado A, van Emmerik REA et al. The effect of footwear and footfall pattern on running stride interval long-range correlations and distributional variability. *Gait Posture* 2016; 44:137–142.
10. Bonacci J, Saunders PU, Hicks A et al. Running in a minimalist and lightweight shoe is not the same as running barefoot: a biomechanical study. *Br J Sports Med* 2013; 47(6):387–392.
11. Fuller JT, Buckley JD, Tsiros MD et al. Redistribution of mechanical work at the knee and ankle joints during fast running in minimalist shoes. *J Athl Train* 2016; 51(10):806–812.
12. Perl DP, Daoud AI, Lieberman DE. Effects of footwear and strike type on running economy. *Med Sci Sports Exerc* 2012; 44(7):1335–1343.
13. Gruber AH, Umberger BR, Braun B et al. Economy and rate of carbohydrate oxidation during running with rearfoot and forefoot strike patterns. *J Appl Physiol* 2013; 115(2):194–201.
14. Jewell C, Boyer KA, Hamill J. Do footfall patterns in forefoot runners change over an exhaustive run. *J Sports Sci* 2016; 35(1):74–80.
15. Fuller JT, Thewlis D, Tsiros MD et al. The long-term effect of minimalist shoes on running performance and injury: design of a randomised controlled trial. *BMJ Open* 2015; 5(8):e008307.
16. Borm GF, Fransen J, Lemmens WA. A simple sample size formula for analysis of covariance in randomized clinical trials. *J Clin Epidemiol* 2007; 60(12):1234–1238.
17. Altman DG, Bland JM. Treatment allocation by minimisation. *BMJ* 2005; 330(7495):843.
18. Esculier JF, Dubois B, Dionne CE et al. A consensus definition and rating scale for minimalist shoes. *J Foot Ankle Res* 2015; 8(42). http://dx.doi.org/10.1186/s13047-015-0094-5.
19. Franz JR, Wierzbinski CM, Kram R. Metabolic cost of running barefoot versus shod: is lighter better? *Med Sci Sports Exerc* 2012; 44(8):1519–1525.
20. Cavanagh PR, Williams KR. The effect of stride length variation on oxygen uptake during distance running. *Med Science Sports Exerc* 1982; 14(1):30–35.
21. Billat V, Sirvent P, Lepretre PM et al. Training effect on performance, substrate balance and blood lactate concentration at maximal lactate steady state in master endurance-runners. *Pflugers Arch* 2004; 447(6):875–883.
22. Cohen J. Quantitative methods in psychology: a power primer. *Psychol Bull* 1992; 112(1):155–159.
23. Hopkins WG, Hawley JA, Burke LM. Design and analysis of research on sport performance enhancement. *Med Sci Sports Exerc* 1999; 31(3):472–485.
24. Miller EE, Whitcome KK, Lieberman DE et al. The effect of minimal shoes on arch structure and intrinsic foot muscle strength. *J Sport Health Sci* 2014; 3(2):74–85.
25. Ridge ST, Johnson AW, Mitchell UH et al. Foot bone marrow edema after a 10-week transition to minimalist running shoes. *Med Sci Sports Exerc* 2013; 45(7):1363–1368.
26. Ryan M, Elashi M, Newsham-West R et al. Examining injury risk and pain perception in runners using minimalist footwear. *Br J Sports Med* 2014; 48(16):1257–1262.
27. McCarthy C, Fleming N, Donne B et al. 12 weeks of simulated barefoot running changes foot-strike patterns in female runners. *Int J Sports Med* 2014; 35(5):443–450.