

Barefoot running improves economy at high intensities and peak treadmill velocity.

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ABSTRACT

Aim. Barefoot running can improve running economy (RE) compared to shod running at low exercise intensities, but data is lacking for the higher intensities typical during many distance running competitions. The influence of barefoot running on the velocity at maximal oxygen uptake ($v\text{VO}_2\text{max}$) and peak incremental treadmill test velocity ($v\text{max}$) is unknown. The present study tested the hypotheses that barefoot running would improve RE, $v\text{VO}_2\text{max}$ and $v\text{max}$ relative to shod running.

Methods. Using a balanced within-subject repeated measures design, eight male runners (aged 23.1 ± 4.5 years, height 1.80 ± 0.06 m, mass 73.8 ± 11.5 kg, VO_2max 4.08 ± 0.39 L \cdot min $^{-1}$) completed a familiarisation followed by one barefoot and one shod treadmill running trial, 2-14 days apart. Trial sessions consisted of a 5 minute warm-up, 5 minute rest, followed by 4 \times 4 minute stages, at speeds corresponding to ~67, 75, 84 and 91% shod VO_2max respectively, separated by a 1 minute rest. After the 4th stage treadmill speed was incremented by 0.1 km \cdot h $^{-1}$ every 15 s until participants reached volitional exhaustion.

Results. RE was improved by $4.4\pm 7.0\%$ across intensities in the barefoot condition ($p=.040$). The improvement in RE was related to removed shoe mass ($r^2=.80$, $p=.003$) with an intercept at 0% improvement for RE at 0.520 kg total shoe mass. Both $v\text{VO}_2\text{max}$ (by $4.5\pm 5.0\%$, $p=.048$) and $v\text{max}$ (by $3.9\pm 4.0\%$, $p=.030$) also improved but VO_2max was unchanged ($p=.747$).

Conclusion. Barefoot running improves RE at high exercise intensities and increases $v\text{VO}_2\text{max}$ and $v\text{max}$, but further research is required to clarify the influence of very light shoe weights on RE.

Key words: $v\text{VO}_2\text{max}$, $v\text{max}$, incremental treadmill velocity

Introduction

The metabolic cost of running is often assessed as the oxygen cost of running, termed running economy (RE). This parameter has an established link to endurance running performance¹. Numerous studies have assessed the effect of barefoot running on RE^{2,3,4,5,6,7,8,9}, with some demonstrating an improvement in RE of 3.1-4.7% in bare-feet compared to shoes^{2,4,6}. Reduced lower-limb mass and the associated decreased limb inertia explain most of this improvement^{2,4}, although total mass reduction¹¹, improved mechanical efficiency⁴, and changes in stride length^{5,8} may also contribute. A lack of RE improvement with barefoot may link to unrepresentative low running speeds or midfoot striking⁸, a metabolic cost of cushioning⁵ or the confounding biomechanics of orthotic wearers³. However, comparisons between barefoot studies have been limited by those not reporting the benefit of total mass reduction to RE¹⁰ by scaling to total mass rather than body mass^{2,4}, not reporting the method of mass scaling^{6,8} or not quantifying the change in RE⁷.

Nevertheless, barefoot RE has typically been assessed at low to moderate running work rates^{2,4,5,8}, which, due to training specific adaptations, may be unrepresentative of RE at the higher intensities often employed in long-distance training and competition^{11,12}. Therefore, it has been suggested that RE should be assessed across a range of work-rates, including higher intensities^{11,12}. Moreover, the predominant influence on barefoot and shod RE differences of shoe mass might be augmented where kinetic energy and limb inertia increase at a rate of velocity squared¹⁰. Higher velocities could also provide higher elastic energy return⁴ and tendon stretch-recoil¹³ barefoot than shod, with an unrestricted foot arch¹⁴. The mass effect may be offset somewhat by a metabolic cost of cushioning (~3%)⁵, speculated to link to the mechanical work of ankle and knee joint adjustments⁹ These

biomechanical adjustments may be in response to higher loading rates and heel pressure barefoot¹⁵ but could be foot-strike dependent¹⁴. However, loading rates that increase similarly with velocity, barefoot and shod¹⁵, do not suggest that velocity would alter the metabolic cushioning cost differential between footwear conditions.

Importantly, the impact of barefoot running on other parameters associated with endurance performance, such as the velocity at VO_2max ($v\text{VO}_2\text{max}$) and peak treadmill speed in an incremental exercise test ($v\text{max}$) has not been examined, despite the observation that these parameters typically display a stronger relationship with endurance running performance than RE^{1,16}. The strong relationship between these parameters and performance likely reflects the fact that both are influenced by RE *and* VO_2max , although $v\text{max}$ may incorporate additional anaerobic or neuromuscular factors¹⁷. However, the extent to which these parameters would be influenced by any change in RE with barefoot running, particularly given the aforementioned potential for intensity-dependent effects, is unknown.

Accordingly, the aims of the present study were to compare between shod and barefoot running, RE across a range of intensities including the higher intensities typical during endurance running competitions, the $v\text{VO}_2\text{max}$ and $v\text{max}$. Further, to examine the relationships between RE changes, $v\text{VO}_2\text{max}$, $v\text{max}$ and shoe mass. It was hypothesised that RE, $v\text{VO}_2\text{max}$, and $v\text{max}$ would improve in barefoot compared to shod running.

Materials and methods

Participants

Eight males participated (age 23.1 ± 4.5 years, height 1.80 ± 0.06 m, mass 73.8 ± 11.5 kg, absolute VO_2max 4.08 ± 0.39 $\text{L} \cdot \text{min}^{-1}$). All participants were regular recreational runners with a minimum of >3 months continuous run training of 45 ± 40 $\text{km} \cdot \text{week}^{-1}$ on a variety of surfaces in the period prior to commencing the experiment. All of the participants wore shoes throughout all of their training and during any competitions, were not experienced barefoot runners, and had no reported illness or injury. Institutional ethical approval and written informed consent were obtained.

Design

A within-subject repeated-measures design was employed, consisting of a familiarisation and two experimental trials (shod and barefoot), undertaken in a balanced order, at the same time of day, 2 to 14 days apart. During shod exercise the participants used their own footwear (none wore orthotics) and were instructed to wear the running shoes that they would use for road races of 5 km to 10 km. All shoes were commercially available running shoes, with shoe mass dictated by a combination of size (from UK size 7.5 to 11.5) and design. Participants consumed the same food and drink on the day preceding the trials, and avoided food for 2 hours and alcohol, caffeine and strenuous exercise for 24 hours beforehand and wore the same clothing (with or without shoes) during the trials. At the outset of each session unshod body-mass was recorded (Seca 770, Germany) and the gas analyser (Cosmed Quark B2, Italy) was calibrated using a 3L syringe with certified

reference gases and ambient air. The same treadmill (Pro-XL, Woodway, USA), set at a 1% gradient¹⁸, was used for all sessions and VO₂, VCO₂, RER, heart rate (Polar T31, UK) recorded throughout exercise.

Methodology

Familiarisation

Shoe-mass was recorded (AND HL-3000LWP, Korea) and participants were familiarised with self-paced sub-maximal barefoot treadmill running for 10 minutes, following which they undertook 4×4 minute running stages in shoes, separated by a 1-minute rest. Stage velocities were estimated to correspond to 50, 60, 70 and 80% VO₂max, based upon recent race times and empirical formulae¹⁹ and were set at intensities lower than those used in the experimental trial to allow for estimation error, which might have prevented completion. After completion of the 4th exercise stage the treadmill velocity was incremented by 0.1 km·h⁻¹ every 6 s and participants continued running until volitional exhaustion, again allowing for estimation error leading to a lack of completion by setting a faster ramp rate than later experimental trials. VO₂max was then determined from trial data.

Experimental trials

Following a standardised warm-up, participants completed 4×4 minute running stages separated by a 1-minute rest at velocities estimated to elicit 70%, 76%, 82% and 88% VO₂max, based upon linear interpolation of the VO₂-treadmill speed relationship and VO₂max obtained using the familiarisation trial data. Rating of perceived exertion (RPE)²⁰ was recorded in the last minute of each stage. Participants continued running after the 4th stage until exhaustion (velocity incremented by 0.1 km·h⁻¹ every 15 s).

Statistical analysis

VO₂ was calculated by linear interpolation between breath by breath VO₂ to 1 s values, then averaged over the last minute of each sub-maximal stage and as the 15 s sequential average²⁴ thereafter. VO₂max was defined by the criteria, no rise in VO₂ despite a rise in velocity, a respiratory exchange ratio ≥ 1.10 , a heart rate within 10 beats per minute of the age-predicted maximum ($209 - 0.7 * \text{age in years}$)²¹ or volitional exhaustion. RE was expressed as the VO₂ per kg of body mass per km of distance²², v_{max} the velocity of the final completed 15 s segment and vVO₂max the lowest velocity at which VO₂max was attained²³. Additional confirmation of vVO₂max was sought from linear extrapolation to VO₂max of the individual velocity-VO₂ relationship (vVO₂max^{est}). Smallest worthwhile changes for RE, vVO₂max and v_{max} were calculated according to Hopkins²⁴.

SPSS-PASW 18.0.0 was used for statistical analysis ($\alpha=0.05$) with data reported as mean \pm standard deviation. Tests for normality (Kolmogorov-Smirnov, Shapiro-Wilk, skewness and kurtosis ratios to standard errors) revealed that RE and RPE data were normal but did not maintain sphericity (Mauchly's test). Accordingly, changes in RE and in RPE were assessed by two-way repeated measures ANOVA (footwear condition x intensity) with the Greenhouse-Geisser statistic and *post-hoc* analysis by pair-wise comparisons. Differences in VO₂max, vVO₂max, v_{max} and body-mass between conditions were assessed by paired samples t-tests and observed powers ($1-\beta$) clarified changes in RE, vVO₂max, v_{max}. Pearson's correlation coefficients determined the relationships between RE, VO₂, vVO₂max, v_{max}, shoe mass, including the mean change in RE across intensities.

Results

Sub-maximal experimental trial stage speeds ranged from 8.1-18.3 km·h⁻¹ and corresponded to 67±5%, 75±6%, 84±4% and 91±5% shod VO₂max. The ANOVA indicated a significant main effect of footwear condition on RE ($F_{(1,0,7,0)}=6.30$, $p=.040$, $1-\beta=.579$) which was improved by an average of 4.4±7.0% in barefoot compared to shod running. *Post-hoc* analysis showed these differences to be significant during the third ($p=.014$) and fourth stages ($p=.012$) where RE was improved by 5.2±5.1% and 3.4±2.9%, respectively (Table 1). Although similar in magnitude, improvements in RE during the first (4.8±9.7%, $p=.095$) and second (4.3±9.3%, $p=.108$) stages were not statistically significant. The ANOVA indicated that the main effect of exercise intensity on RE was not significant ($F_{(1,4,10,1)}=3.0$, $p=.106$). Total shoe mass (0.670±0.191 kg per pair) represented 0.90±0.20% body-mass and was significantly correlated with the improvement in RE during the first ($r=.90$, $p=.003$), second ($r=.76$, $p=.030$), third ($r=.88$, $p=.004$) and fourth stages ($r=.91$, $p=.002$). Overall, the removed shoe mass explained 80% of the variance in the mean improvement in RE for each individual (across intensities) with barefoot running ($p=.003$) (Figure 1). Regression analysis revealed an intercept at 0% improvement for RE at 0.520 kg total shoe mass.

$v\text{VO}_2\text{max}$ improved by 4.5±5.0% (from 16.0±2.2 to 16.6±1.7 km·h⁻¹ ($t_{(7)}=2.40$, $p=.048$, $1-\beta=.536$) and $v\text{VO}_2\text{max}^{\text{est}}$ by 5.8±4.5% with barefoot ($t_{(7)}=-3.58$, $p=.009$). This increase in $v\text{VO}_2\text{max}$ explained 71% ($p=.008$) of the variance in an improvement of 3.9±4.0% in $v\text{max}$ with barefoot (from 16.2±2.1 km·h⁻¹ to 16.8±1.8 km·h⁻¹ ($t_{(7)}=-2.72$, $p=.030$, $1-\beta=.607$), where only one participant reached a higher peak velocity shod (by 0.1 km·h⁻¹). Participants ran for 88±92 s longer barefoot than shod ($p=.030$), but also ran 96±113 s

longer before reaching VO_2max ($p=.047$) with no greater persistence barefoot (-8 ± 60 s, $p=.724$) once VO_2max was achieved. The percentage improvement in RE had a shared variance, but only in the last submaximal stage, of 50% ($p=.049$) with the percentage improvement in $v\text{max}$ and 52% ($p=.044$) with $v\text{VO}_2\text{max}$ improvements. Furthermore, neither the improvements in $v\text{max}$ ($r=.48$, $p=.224$) nor $v\text{VO}_2\text{max}$ ($r=.55$, $p=.137$) were significantly related to shoe mass. The smallest worthwhile changes for RE, $v\text{VO}_2\text{max}^{\text{est}}$, $v\text{VO}_2\text{max}$ and $v\text{max}$ were 2.2%, 3.1%, 2.8% and 2.6% respectively. Neither VO_2max (4.08 ± 0.39 L $\cdot\text{min}^{-1}$ shod vs. 4.10 ± 0.37 L $\cdot\text{min}^{-1}$ barefoot ($t_{(7)}=.34$, $p=.747$)) nor body-mass (73.7 ± 11.5 kg shod vs. 73.9 ± 11.4 kg barefoot ($t_{(7)}=-.60$, $p=.571$)) differed between-conditions. Although RPE increased with exercise intensity ($F_{(1,4,9,6)}=150.6$, $p<0.001$), there were no significant between conditions effects ($F_{(1,0,7,0)}=0.48$, $p=.510$).

Discussion

The main aims of this study were to investigate the effect of barefoot on RE across a range of intensities, including those used in long-distance running training and competition, and to assess the influence of barefoot on $v\text{VO}_2\text{max}$ and $v\text{max}$. Indeed, the improvement in RE observed at the higher exercise intensities in this study is of greater relevance to competitive athletes than those previously reported at lower work rates^{2,4,6}, particularly as the intensities employed in the latter sub-maximal stages are comparable to those reported for all-out 5,000 m running (87.0 ± 5.8 % VO_2max in physical education students and 93.6 ± 3.2 % VO_2max in elite runners²⁵).

The relationship between RE improvement and removed shoe-mass in the present study appears to support previous assertions of a mass effect being the dominant influence on RE

differences^{2,4}, although the wide range of shoe masses used could have aided the strength of the correlation. Whilst within-participant changes in shoe mass were not examined, there is no suggestion that individual RE responses to a given shoe mass might differ^{2,3,4,5,6,7,8,9}. The magnitude of RE improvement that we measured ($4.4\pm 7.0\%$), was at the higher end of those reported previously^{2,4,6}. For instance, Frederick⁹ suggests a 1% improvement in RE per 0.100 kg removed mass *per foot*, which would have equated to an expected improvement in RE of 3.4% in the present study. Moreover, this magnitude of improvement was evident despite a removed total shoe mass in the present study (absolute shoe mass 0.670 ± 0.191 kg; shoe mass as a fraction of body mass of $0.90\pm 0.20\%$), at the lower end of the range where improvements were found in previous studies (absolute shoe mass 0.67-0.70 kg; shoe mass as a fraction of body mass 0.9-1.1%^{2,4,6}). Some difference could be accounted for by previous scaling to eliminate the benefit to RE of total mass reduction⁴ or confounded by the inefficient biomechanics of orthotic wearers² but also limb inertia increasing with the square of velocity¹⁰. However, changes in limb inertia and acceleration due to increasing stride frequency¹⁰ were likely limited across submaximal velocities²⁶. Nevertheless, 20% of the variance in RE improvement remains unaccounted for by shoe mass.

If shoe cushioning differed between participants in the present study then there may have been a variable compensatory metabolic cost⁵ between participants, accounting for some of the variance in RE improvement. Similarly, if some shoes were sub-optimally cushioned compared to those in other studies, an associated cost of cushioning⁵ could have increased the difference between footwear conditions compared to those studies. However, since the present study allowed participants to use their preferred shoes, the findings may have greater external validity than where shoes were provided to participants^{4,5,8}. Indeed, the

presence of an intercept at 0.520 kg (Figure 1) is consistent with an influence on economy beyond shoe mass such as a metabolic cost of cushioning^{5,9}, associated with cushioning treadmill impact forces⁵. This raises the possibility that treadmill RE may be superior in some very lightweight shoes than during barefoot running at high intensities. Alternatively, if the cushioning for the treadmill in the present study was greater than in previous studies it could have provided more of the cushioning otherwise provided by shoes, thereby attenuating the associated metabolic penalty with barefoot. Notably, the present participant with the lightest shoes was more economical shod for this single trial but a running surface of different cushioning²⁷ might be expected to alter the position of the intercept. More speculatively, since the effect of shoe rigidity on RE is unclear⁴, a rigid shoe might inhibit elastic plantar arch structures from providing up to ~17% of energy for the running stance phase²⁸. Shoe design was not controlled in the present study and differing shoe rigidity between participants and an associated restriction of arch flexion¹ could have added to the variance in RE improvement. A greater shoe rigidity than in studies employing different shoe designs could have also augmented the magnitude of this potential detrimental influence on shod RE compared to those studies.

Further novel aspects of the present study were the observation that $\dot{V}O_{2\max}$ and v_{\max} improved with barefoot running whilst $VO_{2\max}$ remained unchanged. The improvement in $\dot{V}O_{2\max}^{\text{est}}$ (5.8%) might be expected, given that RE is used in the calculation of $\dot{V}O_{2\max}^{\text{est}}$. The 50% shared variance between improvements in v_{\max} and RE at 91% $VO_{2\max}$, is consistent with a previously established association but with extra anaerobic or neuromuscular factors relevant to v_{\max} ¹⁷. Although the potential confounding influence of a placebo effect of barefoot on v_{\max} should not be discounted, it appears that v_{\max} gains were achieved largely by delaying the onset of $VO_{2\max}$ since participants did not persist

for longer beyond $v\text{VO}_2\text{max}$ when barefoot. Equally, the absence of significant relationships between shoe mass and changes in either $v\text{VO}_2\text{max}$ or $v\text{max}$ suggests that factors not related to shoe mass were predominantly responsible, yet still favouring barefoot by a similar magnitude to RE (~4%). This may also explain why, despite a delayed VO_2max implying improved economy, RE improvements that were explained 80% by shoe mass, had only a limited shared variance (at 91% of VO_2max) of 52% with improvements in $v\text{VO}_2\text{max}$ and of 50% with $v\text{max}$. Speculatively, these factors could include elastic energy storage¹³, associated mechanical efficiency⁴ or fore-foot striking¹⁴. This could further account for the differential performance of the present participant with the lightest shoes, being more economical shod at submaximal intensities but unable to achieve a higher peak velocity shod, suggesting a need for individual assessment. Nevertheless, a greater contribution to the improved $v\text{VO}_2\text{max}$ and $v\text{max}$ in barefoot may still have been available from limb kinetic energy, at higher velocities than those where RE was assessed¹⁰. Indeed, in contrast to changes in submaximal velocity, approaches to maximal velocity can be characterised by increases in stride frequency rather than stride length²⁶, which might increase the acceleration of the centre of mass of the lower limbs and limb inertia further¹⁰. Similarly, these velocity-related factors could have also contributed to the increased magnitude of improvement in RE that we observed with barefoot running compared to previous studies employing lower velocities^{2,4,6}.

The present study was not without limitation. Given the observed improvement in RE and increases in RPE with intensity, a concomitant change in RPE might have been anticipated, although this was not evident. However, the resolution afforded by a category-ratio scale such as the 15-point RPE scale²⁰ is smaller than the magnitude of change in RE that was observed and future studies should consider utilising perceptual scales with a greater

resolution. Equally, conflicting influences from reduced limb inertia but increased cushioning cost barefoot could have yielded the global measure of RPE inadequate in discriminating between conditions. Although the two-way ANOVA revealed a difference between footwear conditions ($p=.040$, $1-\beta=.579$), the similar sample size to others^{6,8} may have impacted the ability of the *post-hoc* analysis to detect a between conditions difference in RE during the first and second sub-maximal stages. Nevertheless, the mean difference was similar to that recorded at the higher work rates where the difference in RE was statistically significant.

It has been suggested that vVO_{2max} is an important parameter in endurance-running training and performance²⁹. Taking into account the magnitude of improvement in vVO_{2max} and the observation that VO_{2max} can be sustained for ~ 10 minutes²³ it can be estimated that this would equate to the ability to run a further ~ 120 m in the same period during treadmill running. The ergogenic effects of barefoot are further evidenced by the improved $vmax$, itself a 'performance' measure during incremental treadmill running. Indeed, the improvements of 4.4% for RE, 4.5% for vVO_{2max} and 3.9% for $vmax$, exceeded the smallest worthwhile changes (2.2% for RE, 2.8% for vVO_{2max} and 2.6% for $vmax$)²⁴, but caution should be exercised given that RE and vVO_{2max} improvements reported in other studies have exceeded the magnitude of performance improvements by 100-380%^{30,31}. Nevertheless, the improvements observed in the present study were in novice barefoot runners and greater familiarity with barefoot running might augment these improvements, although this speculation should be tempered by the fact that these findings should not be extrapolated to other surfaces beyond the cushioned treadmill surface employed.

Conclusions

The present study has shown improvements in RE at high exercise intensities as well as a faster $v\text{VO}_2\text{max}$ and $v\text{max}$, suggesting a possible ergogenic benefit of barefoot compared to shod running. The improvements in RE appear to be related to the removed shoe mass but this may only apply to heavier shoes for the present running surface. In contrast, the improvements in $v\text{VO}_2\text{max}$ and $v\text{max}$ were of a similar magnitude but were not significantly related to shoe mass. Further research is required to confirm the mechanisms, to identify whether this translates to improved race performance and to clarify the influence of very light shoe weight on RE for various running surfaces.

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TITLE OF TABLE

Table I: Running economy ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) at the four experimental intensities for shod and barefoot running. *denotes a significant difference between conditions ($p<.05$).

TITLE OF FIGURE

Figure 1: Percent change in RE during barefoot running relative to shod running, relative to total removed shoe mass, at velocities corresponding to 67, 75, 84 and 91% shod $\text{VO}_{2\text{max}}$. The regression analysis refers to the relationship between the individual mean improvement (across intensities) in RE with barefoot relative to the individual total removed shoe mass.

| Participant | 67% $\text{VO}_{2\text{max}}$ | | 75% $\text{VO}_{2\text{max}}$ | | 84% $\text{VO}_{2\text{max}}$ | | 91% $\text{VO}_{2\text{max}}$ | |
|-------------|-------------------------------|------------|-------------------------------|------------|-------------------------------|-------------|-------------------------------|-------------|
| | Shod | Barefoot | Shod | Barefoot | Shod | Barefoot | Shod | Barefoot |
| 1 | 224 | 195 | 217 | 205 | 223 | 200 | 218 | 204 |
| 2 | 225 | 200 | 222 | 200 | 215 | 193 | 208 | 197 |
| 3 | 252 | 239 | 243 | 221 | 228 | 215 | 216 | 206 |
| 4 | 205 | 175 | 205 | 184 | 200 | 190 | 199 | 192 |
| 5 | 243 | 229 | 240 | 224 | 233 | 225 | 223 | 217 |
| 6 | 155 | 179 | 160 | 189 | 171 | 180 | 172 | 174 |
| 7 | 236 | 224 | 223 | 210 | 220 | 203 | 218 | 204 |
| 8 | 212 | 212 | 202 | 193 | 212 | 202 | 202 | 202 |
| Mean | 219 | 207 | 214 | 203 | 213 | 201* | 207 | 200* |
| SD | 30 | 23 | 26 | 15 | 20 | 14 | 17 | 13 |

