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Review

Effects of footwear on running economy in distance runners: A meta-analytical review

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ABSTRACT

Objectives: Previous studies reported inconsistent findings about the effects of footwear on running economy, which is a surrogate measure of running performance. This meta-analytical review compared the running economy between running in barefoot, minimalists, and standard running shoes.
Design: Meta-analysis.
Methods: Electronic searches on MEDLINE, CINAHL, SPORTDiscus, and Cochrane Library databases were performed and the reference lists of the screened articles were also scrutinized. Two reviewers screened clinical trials that measured the oxygen cost of runners in different footwear conditions.
Results: Thirteen studies were selected in this meta-analysis with a total of 168 runners included. Barefoot running was shown to be more economic than shod running ($p<0.01$; standardized mean difference = −0.43; 95% Confidence Interval = −0.21 to −0.64; $Z=3.96$). Similar pattern was found when comparing minimalist and shoe ($p<0.01$; standardized mean difference = −0.49; 95% Confidence Interval = −0.29 to −0.70; $Z=4.64$). The observed changes were of small effect. Conversely, no significant difference in the metabolic cost was found between running in minimalists and barefoot running ($p=0.45$).
Conclusions: Barefoot running or running in minimalist may require lower utilization of oxygen than shod running. Theoretically, the lower oxygen cost may improve long distance running performance. However, more than half of the runners in the included studies had previous barefoot experience and the findings may not apply to those habitual shod runners who are undergoing the transition. In addition, high risk of bias was reported in the included studies and quality study in the future is still warranted.

1. Introduction

Most runners in urbanized countries adopted shod running. In the recent decade, there is a growing interest in barefoot running.[1] In view of the fact that decreased plantar surface protection during barefoot running may cause traumatic injuries such as puncture wound,[2] shoe companies have developed barefoot simulating footwear, or minimalist. A recent survey, including 364 recreational, 380 competitive, and 41 elite runners participating running races ranging from 5 km to the full marathon, reported that more than 50% of runners had switched from shod running (SR) to running with minimalists (MR) or barefoot running (BR) partially because of their subjective belief in performance enhancement.[3] Since there is a strong linear correlation between the shoe mass and metabolic cost during distance running,[4,5] it has been suggested that reduction of shoe mass during BR or MR may contribute to the improvement in overall running economy compared to SR. In addition, reports suggested the landing pattern may be changed from heelstrike to non-heelstrike during MR or BR,[1,6,7] the energy exchange in MR or BR may thus be more efficient due to the effective mass difference in these two types of landing pattern,[1] and may result in a better running performance.

Running economy is one of the major determinants for running performance in distance runners.[8–10] Higher running economy indicates that less amount of oxygen is required in submaximal running speed for long distance and hence optimizing the running speed under the same amount of oxygen utilization.[11] Current literature showed inconsistent and inconclusive findings about running economy amongst BR, MR, and SR.[6,12] Such inconsistent and inconclusive findings could be caused by insufficient power and small sample size of the studies. For instance, studies by Squadrone and Gallozzi[13] and Reeves et al.[14] reported improved running economy in barefoot than shod running. However, the effect sizes in these studies were only small to medium (Cohen's d was 0.30 and 0.54,

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respectively). Therefore, a meta-analytical review could help determine the effects of footwear by combining results from different studies. The information about footwear effects on the oxygen consumption may be decisive for running style selection in competitive running population. Therefore, the main objective of this meta-analytical review was to examine the running economy during BR, MR, and SR in distance runners.

2. Methods

This review followed the PRISMA statement for improved reporting of meta-analyses.[15]

An extensive literature search was conducted by two independent reviewers for all clinical studies measuring oxygen consumption during BR, MR, and SR. MEDLINE, CINAHL, SPORTDiscus, and Cochrane Library databases were searched (from inception to November 2014) using different sets of 11 keywords (*VO_2 OR oxygen consumption OR running economy OR metabolic cost AND barefoot OR shoe OR shod OR minimalist OR footwear AND running OR jogging*) with Boolean logic. We defined BR as complete barefoot running i.e. without any structural attachment on the foot. Since the majority of the literature[4,12] have considered sock condition to be representative of barefoot, running with a pair of socks was also regarded as BR. Although there is not a common consensus on the definition of minimalist, we referred to the suggestion by Rixe et al.[16] that footwear of <8 ounce weight (~227 g), heel-toe drop <5 mm, and without additional cushioning padding and artificial support was regarded as MR. Shoe with heavier shoe mass or greater heel-toe drop than the suggested cutoff values would therefore indicate a SR condition.

Studies were included in this review if: (1) the studies presented running economy data for at least one interested footwear conditions and/or barefoot; and (2) the studies were published in a peer-reviewed journal. The exclusion criteria were (1) articles written in languages other than English; (2) articles with recruited sample of any musculoskeletal or neurological disorders, which may affect running pattern or performance; (3) investigations involved experiments taken in a special environment (e.g. in water) or unusual running surface (e.g. running on sand) which may alter the running pattern or performance; (4) evaluation of running economy by an assessment other than a treadmill test; (5) experiments of sprinting or walking; and (6) studies that attached mass to the shoe or foot, as those conditions may not be ecologically valid to reflect actual running condition. Reference lists from published papers were also reviewed in order to identify any other relevant studies not identified in the online databases by manual search. Risk of bias of all eligible studies was assessed by Cochrane Collaboration's tool.[17]

The two reviewers extracted oxygen consumption data from the included articles for further analysis. For incomplete or missing data, authors of the articles were contacted for clarification. All the data from each of the included studies were entered as the means and standard deviations in different conditions. Standardized mean difference and standard error were calculated according to the method suggested by Elbourne et al.[18] and the combined effects were analyzed and illustrated by a forest plot with RevMan version 5.1 using the inverse variance method (The Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen, Denmark). Standardized mean difference of <0.2, 0.2–0.6, 0.61–1.2, 1.21–2.0, and >2.0 indicated trivial, small, moderate, large, and very large effect.[18] The heterogeneity of the included studies was tested by I^2 index. Publication bias was tested by the Egger's regression intercept[19] using Comprehensive Meta-Analysis version 2 (Biostat, Inc., Englewood, New Jersey). A p value of <0.1 (two-tailed) in the test indicated the presence of publication bias.

3. Results

The flow diagram of the process of study selection is shown in Fig. 1. The initial literature search yielded a total of 2328 articles. After removal of 1654 duplicates, 640 irrelevant articles were excluded by title and abstract. For the remaining 34 studies, two studies were excluded as they examined the metabolic cost of people with lower extremity amputation[20] and compared the oxygen consumption difference between males and females.[21] Five studies used mixed samples which may not be representative to distance runners were excluded.[22–26] Two studies compared shoe and orthotics,[27,28] three compared different shoe models,[29–31] three studies investigating short distance running,[32–34] three studies measured oxygen consumption while running on an underwater treadmill,[35–37] and a study comparing running economy on sand[38] were also excluded. Taken together with a thesis report and a study did not provide empirical data,[39] there were a total of 13 reports[4,12–14,40–48] included in this meta-analysis. The total number of participants involved in these studies was 168.

The characteristics of the participants and study designs were summarized in Table 1. The I^2 values were greater than 50% in all comparisons, which indicated high heterogeneity and thus random effect model was employed in all three parts of meta-analysis. Egger's regression intercepts of analysis between BR versus SR, MR versus SR, and BR versus MR were 1.79 ($p = 0.73$, two-tailed), 5.31 ($p = 0.54$, two-tailed), and −9.60 ($p = 0.55$, two-tailed), respectively. These results suggested that publication bias was not present in all the analyses.

All eligible studies adopt a crossover design and produced paired data except one study which was a short-term (4-week) prospective study.[46] Risk of bias assessment is presented in Table 2. Among 13 included studies, most of them did not provide sufficient information regarding randomization, allocation concealment, blinding of outcome assessor, and protocol registration. In addition, the performance bias likely existed as all studies did not blind participants for different running conditions i.e. barefoot versus shod. One study[40] excluded two participants from the analysis without providing a reason and it was at a high risk of reporting bias. Only three studies[14,46,47] arranged different testing sessions on separate days and the other 10 studies examined all testing conditions within the same day.

Out of 168 participants in the included studies, 57 of them had previous barefoot training. Seventy eight of them were habitual shod runners and the status of 33 participants was not reported. Therefore, 73% of the sample was experienced with barefoot running (51% if we assumed the unreported data represented habitual shod runners without any barefoot training). Three out of 13 included studies had mass correction between test conditions[4,12,44] and 4 of them matched landing pattern in different test conditions.[12,43,44,46]

Standardized mean difference in running economy for BR and SR was represented by a forest plot (Fig. 2). The oxygen consumption was shown to be lower in BR when compared with SR ($p < 0.001$; standardized mean difference = -0.43; 95% confidence interval = −0.21 to −0.64; $Z = 3.96$). Similar findings were found in MR when compared with SR ($p < 0.001$; standardized mean difference = −0.49; 95% confidence interval = −0.29 to −0.70; $Z = 4.64$) (Fig. 3). The standardized mean differences were of small effect only. However, the metabolic cost of running between BR and MR was similar ($p = 0.45$) (Fig. 4).

4. Discussion

This meta-analytical review compared the oxygen consumption of runners in different shoe conditions and barefoot in the