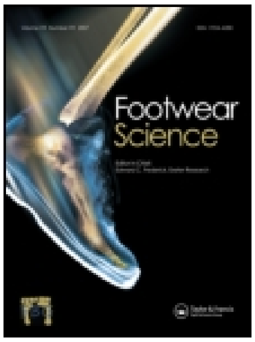

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Improved footwear comfort reduces oxygen consumption during running

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Footwear comfort has been shown to have an influence on injuries, but it was unknown whether comfort was related to performance. The current study examined the effects of footwear comfort on running economy. Thirteen male participants rated five pairs of shoes on perceived comfort. Oxygen consumption was assessed during steady state runs in the least and most comfortable shoes at slightly above the aerobic threshold. A paired *t*-test was used to compare running economy in the most versus the least comfortable shoe conditions. The findings of the study indicated a significant improvement in running economy, 0.7% on average, in the most comfortable shoe condition. It is suggested that future study of kinematic and kinetic reactions to footwear of different comfort will help to understand the mechanism for the observed performance improvement.

Keywords: comfort; running economy; footwear; performance; running

1. Introduction

Comfort is an important aspect for footwear. For example, it has been shown that footwear comfort has an influence on injury. In a prospective study involving 206 military personnel, the incidence of stress fracture and pain was found to be reduced in a more comfortable shoe condition (Mundermann *et al*. 2001). In another study investigating comfort during standing tasks, a preferred footwear condition was shown to relate to the lowest level of lower extremity and back pain (Basford and Smith 1988). In addition to influencing injury, it has been proposed that comfort could relate to performance (Nigg *et al*. 1999, Nigg 2001). However, whether such a link exists has yet to be proven.

Running economy is universally accepted as the physiological measure of distance running performance (Cavanagh and Kram 1985). It is defined as the steady-state oxygen consumption at a given running velocity and represents the global energy expenditure (Conley and Krahenbuhl 1980, Morgan *et al*. 1989). In previous studies, effects of shoe weight, midsole hardness, and midsole bending stiffness have been assessed using running economy (Frederick *et al*., 1982, 1983, 1986, Roy and Stefanyshyn 2006).

The goal of the current study was to determine if footwear comfort is related to athletic performance. More specifically, the purpose of this investigation was to determine if running footwear comfort can influence running economy.

2. Methods

Thirteen proficient male runners (age: 23.8 ± 3.4 years; body mass: 75.2 ± 7.4 kg) provided informed written consent to participate in this study. All participants were physically active and free of lower extremity pain and injury for a minimum of 6 months before the testing.

Five shoe conditions were evaluated to determine the most and least comfortable shoe conditions for the running economy testing (Figure 1). Shoe A was a standard neutral running shoe, the adidas Response. Shoe B was the adidas Response with a carbon fiber plate inserted to increase the longitudinal bending stiffness. Shoe C was the adidas Response with a thin leather insole and an exaggerated arch support. Shoe D was a cross-training shoe (the adidas Flatout) with a flat outsole construction. Shoe E was an inexpensive shoe (Athletic Works) that was not advertised as having any protective features. As shoe mass can have a large influence on running economy (Frederick *et al*. 1982), differences in shoe mass across conditions were eliminated by gluing lead shot to the heel counters. All shoes were provided in a range of sizes (9, 10 or 11 US) to ensure proper fit for the participants.

Overall comfort was assessed for all five shoe conditions. The participants evaluated both static and dynamic comfort in each shoe condition. For the static comfort assessment, the participants rated the following aspects: shoe length, toe box height, forefoot width, midfoot height, arch support, ankle collar height, and

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Figure 1. Five shoe conditions used in the current study.

too low, not acceptable	*low, yet acceptable*	*just right*	*high, yet acceptable*	*too high, not acceptable*
5	3	1	3	5

Figure 2. Example of the categorized rating assigned to each level for the criterion of "Toe box height".

heel hold. The participants then ran on a treadmill at a preferred speed for 5 min after which dynamic comfort was assessed. During this process, the participants rated the following aspects: forefoot cushioning, rearfoot cushioning, forefoot flexibility, stability, heel-to-toe transition, and shoe weight. Five-point scales were used for the rating: "just right" with a rating of 1, "not optimal, yet acceptable" with a rating of 3, and "not acceptable" with a rating of 5 (Figure 2). The average score of the static and dynamic comfort assessments was calculated to determine the most and least comfortable shoe. The shoe with the lowest average rating was selected as the most comfortable shoe and the shoe with the highest average rating was selected as the least comfortable shoe. In the case where two shoe conditions received similar rating (difference ≤ 0.1), the participants were asked to choose an overall preferred shoe between the two. The order in which the participants tried the shoes was randomized. In order to minimize the influence of expectation the participants could have based on visual feedback, all shoes were covered by Neoprene shoe shrouds.

To determine repeatability, a repeat condition was evaluated after the comfort assessments for the five shoe conditions. Thus, each participant actually performed comfort assessments on six shoes. The shoe used for the repeat condition was randomly chosen for each participant. Participants who could not rate comfort level consistently were excluded from the analysis. The following exclusion criterion was set: an average comfort rating difference between the test and retest conditions that exceeded half of the difference between the best and worst shoe conditions. Three participants met this criterion and were therefore deemed unrepeatable and excluded from further analysis. Within the analyzed sample group ($n = 10$), the largest differences found between the first and repeated assessment was 0.71. An intraclass correlation coefficient was calculated to examine the reliability. Furthermore, the most and least comfortable shoes were rated again at the end of the $\dot{V}O_{2max}$ testing session (described in following paragraphs) in order to gain insight on the potential effects of fatigue on comfort assessment. A Pearson correlation coefficient was calculated between the pre- and post-exercise assessments.

Table 1. Overview of the testing schedule.

Week	Task
1	Adaptation to the testing protocol
2	$\dot{V}O_{2max}$ test and comfort assessments
3	Running economy test 1
4	Running economy test 2

An initial adaptation session was performed to allow the participants to become accustomed to running on a treadmill and wearing the $\dot{V}O_2$ data collection equipment before any measurements were performed. This adaptation session was followed by a maximal aerobic power test session a few days later and two running economy tests within a subsequent 14 day period (Table 1).

The ventilatory aerobic threshold, anaerobic threshold and $\dot{V}O_{2max}$ were determined in the maximal aerobic power ($\dot{V}O_{2max}$) testing session for each participant. Data from this test were used to set individual running speeds for the subsequent economy tests for each participant to allow them to perform at a similar physiological intensity. This testing intensity was chosen to be one workload (0.225 m/s) above the aerobic threshold. The participants started off running in their own running shoes at a relatively slow speed. The treadmill velocity was increased by 0.225 m/s at 2-min intervals. When a systematic increase in ventilation occurred near maximal intensity, the treadmill gradient was elevated to 3.0% with a concurrent 0.45 m/s reduction in speed. Thereafter, the treadmill gradient was increased a further 2.0% per minute until exhaustion or $\dot{V}O_{2max}$ criteria had been achieved (CSEP, 2002). The measurement of $\dot{V}O_{2max}$ was calculated using a Sensormedics Horizon Metabolic Cart at 30-s intervals. Calibrations were performed immediately before and following each test using gases of known concentration.

In the following 2 weeks, the participants returned to the laboratory for two economy testing sessions (Williams *et al.* 1991). Each session started with a 10–15-min warm-up period consisting of a gradual increase in running speed approaching the test speed by the seventh minute and variable speeds during the final minutes. In each session, the economy test itself consisted of four steady-state runs in different shoe conditions. To minimize the effects of learning and fatigue, one of the two sessions had the testing sequence of m-l-l-m while the other session had l-m-m-l (where m and l corresponded to the "most" and the "least" comfortable shoe conditions). The sequences used were randomly assigned. As a result, a total of four running economy measurements were performed and averaged for each footwear condition.

Each economy run was of 6-min duration. The initial 4 min allowed the participants to reach a steady state. The $\dot{V}O_2$ values were then measured every 30 s for the last 2 min and were averaged to calculate the mean oxygen consumption for the particular footwear condition. The oxygen consumption values were normalized to time (min) and to participants' body mass (kg). Three-minute rest periods were given between each run to allow changing of shoes and the consumption of water when needed. The three testing sessions were conducted at a similar time of day for each participant to eliminate the potential variation in $\dot{V}O_2$ due to circadium rhythm (Williams 1985, Morgan and Craib 1992, Martin *et al.* 1993).

A one-tailed paired *t*-test was performed to compare the average oxygen consumption between the most and least comfortable shoe conditions ($\alpha = 0.05$). As mentioned previously, three participants were excluded from the analysis as they did not yield reliable comfort assessments.

3. Results

All 10 participants rated shoe A as the most comfortable shoe. The least comfortable shoe varied among the participants. One participant chose shoe E, two chose shoe D, three chose shoe B and four chose shoe C as the least comfortable shoe (Table 2).

The intraclass correlation coefficient test revealed a good reliability (ICC = 0.76) for the repeated comfort assessments. This is similar to what has been reported in previous studies (Mundermann *et al.* 2002, 2003). There was a strong correlation between the pre- and post-exercise comfort assessments ($R^2 = 0.89$, $P < 0.001$) indicating a minimal influence of exercise on comfort perception across the participants (Figure 3). The trend line slope of 0.79 shows that the participants rated all the shoes slightly more comfortable (closer to 1) after running.

Table 2. Comfort rating of the five shoe conditions and the repeated condition. The repeated condition for each participant was randomly selected, and ratings for these conditions were bolded. Columns "Most" and "Least" indicate the selection of the most and least comfortable shoe conditions for each participant.

	Shoe condition							
Participant	A	B	C	D	E	Repeat	Most	Least
1	**1.9**	2.1	3.3	3.8	2.8	1.5	A	D
2	1.0	**2.1**	1.9	1.6	2.9	1.8	A	E
3	1.0	3.4	3.9	3.3	**3.1**	3.1	A	C
4	**1.8**	3.5	2.7	2.1	2.8	2.1	A	B
5	1.6	**2.2**	2.5	2.2	2.4	1.8	A	C
6	1.6	2.7	2.5	**3.6**	1.7	3.0	A	D
7	1.1	1.9	2.1	1.6	**1.9**	1.9	A	C
8	1.8	**2.1**	2.7	2.5	1.8	1.7	A	C
9	1.3	2.9	1.9	3.0	**1.5**	2.2	A	B
10	**1.6**	3.5	1.6	2.4	2.5	1.8	A	B

A significant effect of shoe comfort on $\dot{V}O_2$ was found ($P = 0.036$). Eight out of the ten participants showed a decrease (up to 1.9%) in oxygen consumption for the most comfortable shoe (Figure 4). The mean oxygen consumption was 0.28 ml/kg per min (0.7%) lower for the "most" compared to the "least" comfortable shoe condition.

4. Discussion

Results from the current study showed on average a 0.7% improvement in running economy, when participants ran in the most compared to the least comfortable shoe condition. Studies investigating within-athlete variability in elite track-and-field events indicated that performance enhancements as little as 0.3–0.5% were worthwhile and should be focused on (Hopkins 2005). Although it has yet to be proven whether the improved economy will result in an equivalent performance enhancement, it is reasonable to assume the 0.7% change in running economy is significant for elite runners. It should also be noted that three of the participants had improvements of over 1.5% in running economy with

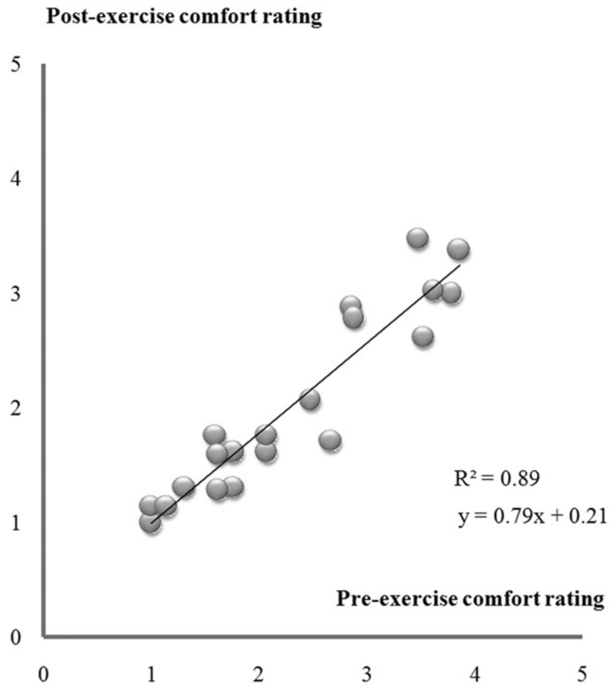

Figure 3. Comfort rating of the most and least comfortable shoe conditions before and after running in the $\dot{V}O_{2max}$ test. The correlation coefficent was calculated based on 20 data points from the 10 participants. Each data point represents the rating of one shoe condition, either the most or least comfortable condition, before and after the exercise.

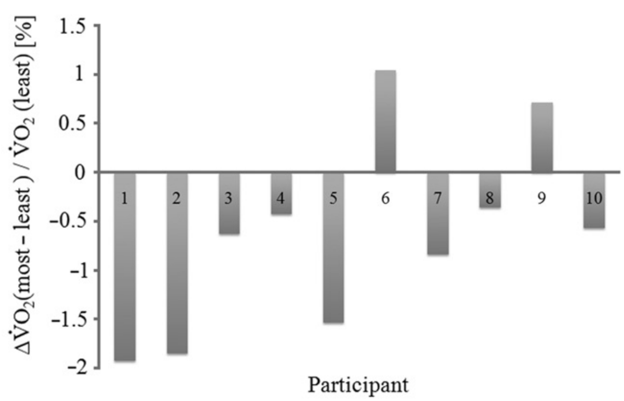

Figure 4. Individual normalized differences in oxygen consumption between the most and least comfortable shoe conditions. Negative values indicate reduced oxygen consumption in the most comfortable compared to the least comfortable shoe.

their most comfortable compared to the least comfortable shoe.

Footwear comfort has been associated with various factors such as foot shape, plantar and dorsal pressure and foot sensitivity (Chen *et al.* 1994, Hawes *et al.* 1994, Mundermann *et al.* 2001, Jordan *et al.* 1997) but these relationships may not be sufficient to explain the effects of comfort on oxygen consumption. In the current study, shoe A, the regular running shoe, was rated as the most comfortable shoe across all participants. Shoe A only differs from shoe B and shoe C on their mechanical variables. However, shoe B and shoe C were each rated as the least comfortable shoe by several of the participants. It may be that mechanical variables are important in explaining comfort and a mechanism relating mechanical variables and comfort (Miller *et al.* 2000) may help explain the changes in running economy.

Comfort has been proposed as an indicator for muscle work (Nigg 2001) and muscle work has been shown to be influenced by modifications to mechanical variables of footwear. Changes on the curvature of the shoe sole have been shown to influence triceps surae activities (Bourgit *et al.* 2008). An unstable shoe design has been found to increase tibialis anterior and gastrocnemius activities (Romkes *et al.*, 2006). Midsole hardness has been shown to relate to pre-activation of the vastus medialis (Nigg *et al.* 1988). Clarke *et al.* (1983) found runners adjusted ankle and knee kinematics when running in shoes with different midsole hardness. In a separate report, the same research group postulated a link between such kinematic adaptations and additional muscle work, and thus the observed differences in running economy (Frederick *et al.* 1983). Recently, the relationship between perceived comfort and lower extremity kinematic and kinetic variables and muscle activity was investigated. It was found that comfort could be partially explained by several kinematic, kinetic and EMG variables. In addition, the majority of these variables were related to the activity of the tibialis anterior and peroneous longus muscles (Mundermann *et al.* 2003).

It is universally accepted that local muscle activities are in direct relationship with global oxygen consumption. Thus, the relationship found between footwear modifications, muscle work and perceived comfort may help explain the current finding of lower oxygen consumption in the most comfortable shoe condition.

There are two main limitations to the current study. First is that, despite the good correlation observed between the pre- and post-exercise ratings, comfort assessed in the current study was rather short-term. A longer adaptation period may help improve the validity of the comfort measurements. The second limitation is that lower extremity kinematics, kinetics, and EMG were not collected; thus the mechanism explaining why and how comfort and oxygen consumption is related cannot be provided.

In conclusion, comfort has a significant influence on distance running performance. However, future work is needed to determine the underlying mechanism.

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