Does enhanced footwear comfort affect oxygen consumption and running biomechanics?

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Abstract

Comfort as an essential parameter for running footwear is gaining importance in footwear research and development, and has also been proposed to decrease injury rate and improve metabolic demand in the paradigm of the comfort filter. The aims of this study were to determine differences in oxygen consumption and biomechanical variables associated with lower extremity injuries in response to running shoes of differing comfort. Fifteen male runners attended two testing sessions including an incremental lactate threshold test, a comfort assessment and treadmill running trials for the biomechanical and physiological measurements. Statistical analyses were performed on oxygen consumption, spatio-temporal variables including foot-ground angle and coupling angle variability of 12 couplings in five stride phases. No decrease in oxygen consumption was found in the most preferred shoe condition. Investigation of potential biomechanical contributors to changes in metabolic demands revealed differences in the stride rate between the most and least preferred condition. In coupling angle variability analyses, only one coupling (ankle dorsiflexion/plantarflexion to knee varus/valgus) yielded a significant difference between conditions in the phase including the touch down. Based on the findings of this study, previous suggestions regarding positive effects of enhanced footwear comfort during running cannot be supported – neither on economy nor on injury prevention perspective. However, a prospective study of lower extremity injury combined with measurements of biomechanical and physiological variables seems to be required for a definite support or contradiction of the comfort filter.

Keywords: Analysis, biomechanics, dynamical systems, health, physiology

Highlights

- According to the paradigm of the comfort filter, comfortable footwear positively affects running economy and decreases lower extremity injury risk.
- Based on analyses of oxygen consumption and biomechanical variables during treadmill running in shoes of differing comfort, no support for the paradigm of the comfort filter could be provided.
- Potential beneficial effects of enhanced footwear comfort are highly individual and should be subject to further investigations.

Introduction

The preferred movement path (PMP) as a predefined joint movement trajectory has been proposed to explain only minimal changes in kinematic parameters in response to footwear interventions (Nigg, 2010; Nigg & Wakeling, 2001; Nigg, Baltich, Hoerzer, & Enders, 2015). Joint mechanics and motor control therefore seem to dictate a path of least resistance for a given task. The use of footwear intended to maintain individual PMP could lead to a reduction of injury rate and minimisation of metabolic demand due to decreased muscle activation and a sensation of comfort (Nigg, 2010; Nigg et al., 2015). Accordingly, subjective comfort is often viewed as an essential factor in sport shoe development (Nigg, 2010). The comfort filter is a proposed paradigm that assumes that a running shoe selected based on perceived comfort will facilitate the PMP, potentially reduce injury risk (Nigg et al., 2015) and improve running economy (Nigg, 2010). Evidence supporting the comfort filter...
has been provided with regard to locomotion-related injuries (Mündermann, Stefanyshyn, & Nigg, 2001) and oxygen consumption (Luo, Stergiou, Worobets, Nigg, & Stefanyshyn, 2009).

One study showed reduced oxygen consumption levels during running at submaximal speed in shoes that were subjectively rated as most comfortable (Luo et al., 2009). This lends initial support to the proposed comfort filter paradigm with respect to running economy. Nigg (2010) proposed that one aspect of the decreased metabolic demand might be due to a reduction of muscle activation. However, definite determinants and the mechanisms of the reduction in oxygen consumption during running in comfortable footwear detected by Luo et al. (2009) are not well understood to date. Potential contributors to reductions in metabolic demands might be comfort induced changes in spatio-temporal variables (e.g. stride length, stride frequency, ground contact time and vertical oscillation of the centre of mass), since these were shown to influence oxygen consumption (Cavanagh & Williams, 1982; Morgan, Martin, & Krahenbuhl, 1989; Nummela, Keranen, Santos-Concejero et al., 2014). The results in the running economy (Di Michele & Merni, 2014; Saunders, Pyne, Telford, & Mikkelsson, 2007; Saunders, Pyne, Telford, & Hawley, 2004). Furthermore, a change in strike pattern and therefore foot-ground angle might induce differences in oxygen consumption measures, since lower foot-ground angles (forefoot and midfoot strikers) were previously associated with increased running economy (Di Michele & Merni, 2014; Santos-Concejero et al., 2014). The results in the study by Luo et al. (2009) are influenced by an unbalanced distribution of preferences among the test shoes since all participants ranked the same shoe condition (standard neutral running shoe) as the most comfortable. The shoes provided in the study included standard neutral running shoes and shoes that were equipped with non-standardised features developed for particular practitioners (i.e. carbon fibre plates for increased longitudinal bending stiffness, exaggerated arch support and a cross training shoe). These particular features might be responsible for the inequality in comfort distribution among the test shoes. Therefore, the mechanical properties of footwear rather than comfort could be responsible for the reduced oxygen consumption observed by Luo et al. (2009). The effects of comfort on oxygen consumption in shoes with a balanced distribution of preferences (i.e. the most and least preferred conditions of the participants are spread across the test conditions) need to be investigated.

The long-term use of comfortable inserts in military personnel have resulted in reduced injury rates of the foot, ankle, knee, hip and lower back compared to a control group (Mündermann et al., 2001). While anthropometrics and sensory factors have been identified as potential influences to variation in comfort perception among individuals (Miller, Nigg, Liu, Stefanyshyn, & Nurse, 2000; Mündermann et al., 2001), the mechanisms leading to the decrease in injury rate in individually comfortable footwear remain unknown. Potential explanations are changes in functional biomechanical parameters (e.g. pressure distribution, muscle activity or joint dynamics) that have been shown to be influenced by the comfort of footwear (Che, Nigg, & de Koning, 1994; Dinato et al., 2015; Jordan & Bartlett, 1995; Mills, Blanch, & Vicenzino, 2012; Mündermann, Nigg, Humble, & Stefanyshyn, 2003, 2004), even though those parameters were not intended to be linked to injury risk in the aforementioned investigations. However, the differences in the latter studies could only be partially attributed to the differences in comfort (e.g. 35% of comfort differences were explained by changes in 15 biomechanical variables including kinematics, EMG intensity and joint forces and moments; Mündermann et al., 2003). Furthermore, most of the latter investigations have been conducted on orthotic comfort rather than footwear comfort in general. With regard to the decrease in injury rates proposed within the paradigm of the comfort filter, a profound knowledge base needs to be built by investigating changes in biomechanical variables during running in shoes of differing comfort (Dinato et al., 2015; Jordan & Bartlett, 1995).

Functional biomechanical variables previously defined as potential indicators of injuries in the lower extremities are measures of coordination variability (e.g. the coupling between ankle inversion/eversion to knee internal/external rotation in joint couplings and foot inversion/eversion to shank transversal rotation in segment couplings; Cunningham, Mullineaux, Noehren, Shapiro, & Uhl, 2014; DeLeo, Dierks, Ferber, & Davis, 2004; Hamill, Palmer, & Van Emmerik, 2012; Hamill, van Emmerik, Heiderscheit, & Li, 1999; Heiderscheit, Hamill, & van Emmerik, 2002; Miller, Meardon, Derrick, & Gillette, 2008; Rodrigues, Chang, TenBroek, van Emmerik, & Hamill, 2015). It is speculated that changes in coordination variability could further serve as an injury predictor (Cunningham et al., 2014; Hamill et al., 1999). In the case of changes in coordination variability by wearing shoes of differing comfort, this potential predictor could contribute to decreased injury rate in comfortable footwear. However, evidence that the comfort of footwear influences coordination variability is lacking.

Even though the effects of comfort on biomechanics and physiology have been shown in previous investigations, the paradigm of the comfort filter (Nigg et al., 2015) is mainly based on two studies focussing specifically on running economy (Luo et al., 2009) and injury risk in military personnel.
(Mündermann et al., 2001). The current knowledge base requires additional work to either support or contradict the paradigm. Accordingly, the overall purpose of this study is to investigate the potential response to shoes of differing comfort regarding metabolic demand along with potential mechanisms and functional biomechanical variables associated with injury risk. The corresponding specific aims are (1) to determine potential differences in oxygen consumption and biomechanical variables that might explain changes in metabolic demand (spatio-temporal variables including foot-ground angle) and (2) to determine potential differences in coordination variability (i.e. segment couplings) that has been associated with lower extremity injuries in previous studies. Based on preceding investigations it is hypothesised that an increase in comfort will result in a decrease in oxygen consumption along with changes in spatio-temporal variables including foot-ground angle and higher coordination variability.

**Material and methods**

**Participants**

Fifteen experienced male runners (26 ± 4 yrs, 183 ± 5 cm, 79 ± 8 kg) provided written informed consent prior to participation in this study that was approved by the Institutional Ethics Committee. A minimum of 20 km/week of running and experience in treadmill running was required for inclusion in the study. Predefined exclusion criteria were musculoskeletal or cardiovascular diseases and injuries of the lower extremities.

**Footwear conditions**

Five footwear conditions varying in mechanical properties were provided for this study. The set of shoes used in the current study was assumed to produce different comfort ratings based on criteria previously reported (Hoerzer, Trudeau, Edwards, & Nigg, 2016; Lindorfer, Kröll, & Schwameder, 2019; Mills, Blanch, & Vickers, 2010; Nigg et al., 2015). The shoe conditions in the current study showed ranges in mechanical properties of 80 g (total mass), 3.7 mm (heel lift), 87 N mm⁻¹ (forefoot cushioning), 145 N mm⁻¹ (rearfoot cushioning), 0.0035 N m rad⁻¹ (forefoot bending) and 0.007 N m rad⁻¹ (rearfoot bending). Since shoe mass influences oxygen consumption by approximately 1% per 100 g of additional mass (Franz, Wierzbinski, & Kram, 2012; Frederick, 1984) the difference in total mass between the test shoes in this study was compensated by gluing lead to the heel counters as described in Luo et al. (2009).

**Determination of individual running speed**

A lactate step test was conducted prior to the actual economy and biomechanics testing session for determining the individual’s running speed at 2 mmol l⁻¹ lactate concentration, analysed with a Biosen S-Line analyser (EKF Diagnostics, Magdeburg, Germany). Participant information was provided in accordance with the recommendations by Compher, Frankenfield, Keim, and Roth-Yousey (2006) regarding physical activity restrictions and meals. The lactate step test was performed on a treadmill (Pulsar It 3p, h/p/cosmos sports & medical Ltd., Nussdorf-Traunstein, Germany) starting at a speed of 6, 7.5 or 9 km h⁻¹ depending on individuals’ fitness level and increased by 1.5 km h⁻¹ every 5 min until exhaustion. Blood lactate measurements were taken at the end of each stage.

**Comfort assessment**

All participants started with a 5 min warm up on the treadmill at a self-selected speed. Shoes were subsequently ranked based on “overall comfort” in pairwise comparisons at each individual’s submaximal running speed determined by lactate step test (11.3 ± 1.7 km h⁻¹). To prevent subjective ratings of the shoe design, the participants were blinded to the test shoes by a folded sleeping mask. The five shoe conditions were randomly paired (10 pairs) to assure for comparisons of each test condition to all other conditions. The participants provided a preference or equality in comfort in the respective comparison, resulting in points corresponding to the preference (1 for the preferred condition, 0 for the non-preferred condition or 0.5 for both if the shoe conditions were considered equal in comfort). The sum of points after all comparisons yielded the ranking of the shoes. Shoe preference for each comparison was assessed after two minutes of treadmill running in both conditions. Additionally, participants rated difference in comfort between their most preferred (MP, rank 1) and least preferred (LP, rank 5) condition via a 100 mm Visual Analogue Scale (VAS). A participant-derived approach of evaluating the subjective meaningful difference in comfort (SMD) on the VAS was conducted according to Mills et al. (2010). Participants were therefore asked to select a value left or right of a pre-determined value on the VAS at a distance that indicated a subjective relevant change in comfort. This allowed for interpretation of the VAS difference between the two conditions. The MP and LP condition were selected for each participant for the subsequent economy and biomechanics data collection.
Economy and biomechanics data collection

Two six minute running trials were performed for both the MP and LP conditions. A shoe order of MP-LP-LP-MP or LP-MP-MP-LP, randomised among participants, was chosen to minimise the effects of learning and fatigue (Luo et al., 2009). A rest period of two minutes was provided between the running trials in order to change footwear. The first four minutes of each running trial were provided for participants to reach steady-state oxygen consumption (Luo et al., 2009), while data from minute four to six were used for further post-processing. Oxygen consumption was measured breath-by-breath throughout the trial by a metabolic system (K5, COSMED, Rome, Italy) that was calibrated with gases of known concentration.

Reflective skin markers were attached to the lower extremities according to the Cleveland Clinic marker set (Motion Analysis Corp., Santa Rosa, USA) with additional markers on the shoes. Three-dimensional kinematic data were captured by a 12 camera infrared motion capture system at 250 Hz (Vicon, Oxford Metrics Ltd, Oxford, UK). Four sequences of ten strides each were taken from the last two minutes of each running trial.

Data analysis

In addition to the shoe selection based on the ranking assessment, VAS data were analysed in terms of average absolute differences [mm] and average relative difference [SMD] between the conditions. The average relative difference corresponds to the absolute difference in VAS values between MP and LP condition divided by the individuals’ subjective meaningful difference in comfort according to Mills et al. (2010).

Oxygen consumption data [ml kg$^{-1}$ min$^{-1}$] from the last two minutes of each trial were averaged, resulting in two oxygen consumption values in both MP and LP conditions. The total oxygen consumption was obtained by averaging these two values per condition. One participant was excluded from the analysis of oxygen consumption due to technical issues in the measurement device.

Marker trajectories were filtered using a fourth order zero-lag butterworth filter with cut-off frequencies between 8 and 30 Hz, determined by residual analyses (Winter, 2009). Detection of gait events was based on position and acceleration data of markers attached to the shoes (Maiwald, Sterzing, Mayer, & Milani, 2009).

To investigate mechanisms of potential changes in oxygen consumption in response to shoes of different comfort, spatio-temporal variables (including foot-ground angle) that were associated with metabolic changes in previous studies (stride length, stride frequency, ground contact time and the vertical oscillation of the centre of mass; Cavanagh & Williams, 1982; Morgan et al., 1989; Nummela et al., 2007; Santos-Concejero et al., 2014; Saunders et al., 2004) were calculated in Visual 3D (Version 5, C-Motion Inc., Rockville, MD, USA) and Matlab (R2015b, Mathworks Inc., Natick, MA, USA).

Coupling angles associated with lower extremity injury (patello-femoral pain and ili-tibial band syndrome) or fatigue in previous investigations (Cunningham et al., 2014; Ferber & Pohl, 2011; Hamill et al., 1999; Heiderscheit et al., 2002; Miller et al., 2008) were calculated according to Needham, Naemi, and Chockalingam (2014) based on a modified vector coding technique introduced by Heiderscheit et al. (2002). An inverse kinematics pose algorithm in Visual 3D followed by custom processing routines in Matlab allowed for the extraction of joint angles and segment orientations. The vectors between two adjacent points in the angle-angle plot were determined and the angle of the vector to the horizontal represents the coupling angle (Figure S1a). The 12 coupling angles considered for this study are explained in Table I. Coupling angle variability (CAV), as shown in (Figure S1b) was obtained from circular statistics according to Needham et al. (2014). The CAV, based on 80 strides per participant and condition, was analysed for the entire stride, five functional phases of the stride (Q1: 11–30% of stride, Q2: 31–50% of stride, Q3: 51–70% of stride, Q4: 71–90% of stride, Q5: 91% to 10% of the next stride; Needham et al., 2014) and for the stance phase only.

Table I. Analysed joint and segment couplings in the lower extremities.

| Coupling     | Definition                                           |
|--------------|------------------------------------------------------|
| AI_KF        | ankle inversion/eversion to knee flexion/extension  |
| AD_KF        | ankle dorsiflexion/plantarflexion to knee flexion/extension |
| AI_KV        | ankle inversion/eversion to knee varus/valgus       |
| AD_KV        | ankle dorsiflexion/plantarflexion to knee varus/valgus |
| AI_KR        | ankle inversion/eversion to knee internal/external rotation |
| AD_KR        | ankle dorsiflexion/plantarflexion to knee internal/external rotation |
| FI_SR        | foot inversion/eversion to shank transversal rotation |
| FI_TA        | foot inversion/eversion to thigh abduction/adduction |
| SR_TF        | shank transversal rotation to thigh flexion/extension |
| SR_TA        | shank transversal rotation to thigh abduction/adduction |
| SR_TR        | shank transversal rotation to thigh transversal rotation |
| SF_TF        | shank flexion/extension to thigh flexion/extension  |
Descriptive distribution analysis between MP and LP condition among the five test shoes was performed and absolute and relative VAS differences between the two selected conditions were depicted.

Statistical analyses of oxygen consumption, foot-ground angle, spatio-temporal variables and CAV measures included a confirmation of normality by Shapiro-Wilks tests. Paired t-tests were performed between the MP and LP condition. Wilcoxon tests were used in cases of non-normal distribution. The level of significance was set to $\alpha = 0.05$ for all statistical analyses. Additional effect sizes (Cohen’s $d_z$; Cohen, 1988) are provided as a measure of relevance.

**Results**

The MP condition was fairly balanced among the provided test shoes, while the LP condition was unevenly distributed among the shoes A–E. The number of participants choosing the respective shoe as (MP/LP) condition was as follows: shoe A (3/0), shoe B (5/1), shoe C (3/1), shoe D (2/9) and shoe E (2/4). The average absolute difference between MP and LP in rating on the VAS was $57 \pm 25$ mm (Figure 1). Referring to the reported subjective meaningful change in comfort (SMD), the relative difference between the two conditions was $4 \pm 2$ times the SMD.

In analysis of oxygen consumption, the MP condition ($44.4 \pm 8.9$ ml min$^{-1}$ kg$^{-1}$) did not significantly differ from the LP condition ($44.2 \pm 9.0$ ml min$^{-1}$ kg$^{-1}$, $p = 0.20$) with a low effect size of $d_z = 0.36$. Individual analysis revealed normalised differences between $-1.3$ and $4.3\%$ (Figure 2) with positive values indicating higher oxygen consumption values in the MP condition.

Stride frequency was lower in the MP condition compared to the LP condition (MP: $1.32 \pm 0.07$, LP: $1.33 \pm 0.07$, $p < 0.05$, $d_z = 0.57$). No significant differences were detected for stride length (MP: $2.38 \pm 0.34$ m, LP: $2.37 \pm 0.34$ m, $p = 0.07$), ground

Figure 1. Mean VAS score and individual values for LP and MP in each participant. The horizontal bars represent the subjectively reported meaningful difference in comfort. Note: Comfort assessments of LP and MP as well as the SMD were conducted using separate sheets during data collection.

Figure 2. Normalised difference in oxygen consumption between the MP and LP conditions for each participant. Note: One participant was excluded from the analysis due to technical issues.
contact time (MP: 0.29 ± 0.04 s, LP: 0.29 ± 0.04 s, \( p = 0.90 \)) and vertical oscillation of the centre of mass (MP: 0.09 ± 0.02 m, LP: 0.09 ± 0.02 m, \( p = 0.20 \)). Similarly, the foot-ground angle was not significantly different in the MP and LP condition (MP: 20 ± 5°, LP: 19 ± 6°, \( p = 0.71 \)).

Exemplary angle-angle plots, corresponding coupling angles, and CAV are depicted for two participants in Figure S2. The average and standard deviation of CAV among all participants was similar for both conditions (Table II). No statistical differences between MP and LP condition were obtained for the investigated CAV measures (Table I) across the entire stride and the stance phase. Splitting the stride into five phases resulted in a significant difference of AD_KV within Q5 (phase including heel strike) and a moderate effect size of \( d_{z} = 0.71 \). All other comparisons of CAV in MP and LP condition within the five stride phases were not statistically different.

### Discussion

Comfort as an essential parameter for running footwear is important for footwear research and development (Nigg, 2010). The paradigm of the comfort filter (Nigg et al., 2015) substantiates this focus in footwear development by associating comfort perception to running economy (Luo et al., 2009) and injury risk (Mündermann et al., 2001). However, a well-founded base of investigations for this paradigm is still lacking. This study therefore aimed to investigate comfort effects with regard to oxygen consumption (economy perspective) and biomechanical parameters (injury perspective). Based on the main findings of this study, the paradigm of the comfort filter cannot be supported since an increase in comfort did not lead to decreased oxygen consumption and significant changes in biomechanical variables.

### Comfort assessment

The selection of shoes ranked most and least comfortable, in combination with substantial absolute and relative differences in VAS ratings allowed for investigation of non-random effects of footwear differing in comfort. The relative difference of 4 times the reported subjective meaningful change in comfort (SMD) between the conditions indicated that the selected shoes as extreme examples were appropriate for studying short-term comfort effects.

In selection of the MP and LP conditions based on the ranking of overall comfort, the distribution among the test shoes was not balanced in the LP condition (MP: 20 ± 5°, LP: 19 ± 6°, \( p = 0.71 \)).

A similar distribution among the test shoes was observed in the study of Luo et al. (2009), the same shoe was ranked as MP condition for all participants. The "no insert" condition in the study of Mündermann et al. (2001) was rated lowest on average and ranked as least comfortable by the majority of participants. Comfort effects in terms of reduced injury risk are therefore potentially biased by the intervention of inserts compared to the control condition. Studies on comfort effects require a balanced distribution among test shoes to...
avoid bias of the different mechanical characteristics. One approach for study designs might therefore be to analyse a non-random sample of the study with regard to a balanced distribution of conditions.

Inconsistent comfort assessments are a remaining challenge in studies on comfort effects and further in comparisons of studies. Luo et al. (2009) calculated the ranking from the average across various comfort items in static and dynamic measurements. Since the reliability of comfort assessments is item-specific (Lindorfer et al., 2019), an “overall comfort” ranking was provided in the current study, which was shown to yield the highest reliability in comfort assessments (Lindorfer et al., 2019; Mills et al., 2010). However, differences in the interventions investigated and the challenge of reliable comfort ratings in long-term assessments (Hoerzer et al., 2016; Mills et al., 2010; Münndermann, Nigg, Stefanyshyn, & Humble, 2002) impede investigations on comfort effects.

Oxygen consumption and spatio-temporal variables including foot-ground angle

No significant differences in oxygen consumption were found between the MP and LP condition. Therefore, the hypothesis of increased running economy in comfortable footwear was rejected. Since no differences in oxygen consumption were observed, no changes in spatio-temporal variables including foot-ground angle as a potential explanation of the hypothesised decrease in oxygen consumption could be expected. Stride frequency was shown to be decreased in comfortable footwear conditions. A functional explanation might be that the decreased stride frequency is closer to the individual optimal stride frequency that was shown to decrease oxygen consumption (Saunders et al., 2004; Tartaruga et al., 2012). However, this was not covered by the current study. Individual analyses of oxygen consumption (Figure 2) revealed substantial differences in the size of the comfort effect. Only half of the participating group yielded a decrease in oxygen consumption when wearing the MP condition. One participant increased oxygen consumption by 4% in the MP condition. This is greater than the differences obtained in previous studies of footwear interventions (Frederick, Howley, & Powers, 1986; Luo et al., 2009; Nigg, Stefanyshyn, Cole, Stergiou, & Miller, 2003). Individual normalised differences of up to 3% were found when comparing shoes of different bending stiffness (Roy & Stefanyshyn, 2006). However, the increase of 4% seemed questionably high for an experienced runner, since even small differences in oxygen consumption were found worthwhile to focus on in elite track and field athletes (Hopkins, 2005).

Based on the theory of PMP, the dictated movement path would allow for minimal variability in coordination patterns. Therefore, in contrast to a desirable increase in CAV for minimisation of injury risk, a decrease in CAV could be favourable for an increase of running economy. However, a detailed analysis including EMG would be required for the investigation of relationships between CAV and running economy.

Referring to the majority of participants selecting shoe D as LP condition, an additional analysis revealed that those participants did not yield similar results in oxygen consumption differences. Therefore, the unevenly balanced distribution might not have biased the analyses with regard to the mechanical characteristics of the shoes. It remains unknown, if different mechanical characteristics were responsible for the improved running economy observed by of Luo et al. (2009), since all participants in the latter study chose the same shoe as MP condition and mechanical characteristics were shown to influence oxygen consumption (Frederick et al., 1986; Nigg et al., 2003; Roy & Stefanyshyn, 2006). Contradicting the findings of Luo et al. (2009), footwear comfort is not decisive for running economy based on the results of the current study.

Coordination variability

In addition to running economy, the paradigm of the comfort filter proposed a decrease in injury risk (Münndermann et al., 2001; Nigg et al., 2015). Even though the long-term assessment in the study of Münndermann et al. (2001) revealed decreased injury rates for the lower back and the lower extremities, this study was conducted in the context of military personnel which was provided with different shoe inserts. Evidence for potential differences in biomechanical parameters resulting from running footwear of different comfort is still lacking, especially with regard to functional parameters like coordination variability that indicate injuries.

Intra-individual differences in the couplings investigated indicated changes in coordination mechanics in response to the two conditions (Figure S2). However, since no differences in CAV measures in group analyses were obtained in this study (except for one coupling in Q5), no effects of footwear comfort can be provided with respect to coordination variability. Even substantial differences in comfort did not lead to differences in the investigated coordination parameters. The hypothesis of decreased CAV values in the LP condition was therefore rejected.
CAV as a dynamic system approach provides an analysis of the proposed critical interaction between segments, rather than the segments itself (Hamill et al., 2012). In contrast to traditional macroscopic analyses of joint angles, CAV could therefore be determined as an indicator of injuries (Cunningham et al., 2014; Heiderscheit et al., 2002) and was speculated to be a predictor of lower extremity injuries. Footwear of different comfort that could be expected to differ in injury risk (Mündermann et al., 2001), yielded no significant differences in CAV in the current study, though. The observations of similar kinematics in shoes of different comfort support the PMP theory (Nigg et al., 2015; Nigg, Mohr, & Nigg, 2017). Participants thereafter follow a predefined path even in footwear differing regarding mechanical characteristics and regarding comfort by adjusting muscle activation. However, specific EMG measures are required for further evidence.

In absence of differences in biomechanical parameters based on injury indication in previous studies (Cunningham et al., 2014; DeLeo et al., 2004; Hamill et al., 1999; Hamill et al., 2012; Heiderscheit et al., 2002; Miller et al., 2008; Rodrigues et al., 2015), no further evidence can be provided that comfortable running footwear is favourable considering injury rate. Even though expanding sample size and analyses in terms of EMG measures could give insight to potential variations due to comfort interventions, a prospective epidemiological study would be required for investigating injury rates in footwear differing in subjective comfort. However, since to date there is no conclusive support that comfort of running footwear influences physiological and biomechanical parameters, a profound justification for a prospective study on injury rates in comfortable footwear is still lacking. Although effects of footwear comfort were obtained in different settings (Che et al., 1994; Kinchington, Ball, & Naughton, 2011; Luo et al., 2009; Mills et al., 2012; Mündermann et al., 2001; Mündermann et al., 2003, 2004), the current study does not lend support for the paradigm of the comfort filter and it is therefore still on vague foundation since it is supported by only a few studies.

Conclusion
The beneficial effects of enhanced footwear comfort as proposed in the paradigm of the comfort filter cannot be supported by the findings in this study. Even though some individuals showed reduced metabolic demands during running in the MP condition, generalised positive effects of comfortable footwear have to be contradicted. However, conclusions about injury rates could not be made in the current study. Although well-founded indication for reduced injury rates is missing, a long-term study on running shoes of differing comfort with additional assessment of biomechanical and physiological measures seems to be required for further enhancement of the knowledge base of comfort effects and overarching support or contradiction of the concept of comfort filter.

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References
Cavanagh, P. R., & Williams, K. R. (1982). The effect of stride length variation on oxygen uptake during distance running. Medicine & Science in Sports & Exercise, 14(1), 30–35.
Che, H., Nigg, B. M., & de Koning, J. (1994). Relationship between plantar pressure distribution under the foot and insole comfort. Clinical Biomechanics, 9(6), 335–341. doi:10.1016/0268-0033(94)90062-0.
Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). Hillsdale: Lawrence Erlbaum Associates.
Compher, C., Frankenfield, D., Keim, N., & Roth-Yousey, L. (2006). Best practice methods to apply to measurement of resting metabolic rate in adults: A systematic review. Journal of the American Dietetic Association, 106(6), 881–903.
Cunningham, T. J., Mullineaux, D. R., Noehren, B., Shapiro, R., & Uhl, T. L. (2014). Coupling angle variability in healthy and patellofemoral pain runners. Clinical Biomechanics, 29(3), 317–322.
DeLeo, A. T., Dierks, T. A., Ferber, R., & Davis, I. S. (2004). Lower extremity joint coupling during running: A current update. Clinical Biomechanics, 19(10), 983–991. doi:10.1016/j.clinbiomech.2004.07.005.
Di Michele, R., & Merni, F. (2014). The concurrent effects of strike pattern and ground-contact time on running economy. Journal of Science and Medicine in Sport, 17(4), 414–418.
Dinato, R. C., Ribeiro, A. P., Butugan, M. K., Pereira, I. L., Onodera, A. N., & Sacco, I. C. (2015). Biomechanical variables and perception of comfort in running shoes with different cushioning technologies. *Journal of Science and Medicine in Sport, 18* (1), 93–97. doi:10.1016/j.jsams.2013.12.003.

Ferber, R., & Pohl, M. B. (2011). Changes in joint coupling and variability during walking following tibialis posterior muscle fatigue. *Journal of Foot and Ankle Research, 4*, 6. doi:10.1186/1757-1146-4-6.

Franz, J. R., Wierzbinski, C. M., & Kram, R. (2012). Metabolic cost of running barefoot versus shod: Is lighter better? *Medicine & Science in Sports & Exercise, 44*(8), 1519–1525.

Frederick, E. C. (1984). Physiological and ergonomics factors in running shoe design. *Applied Ergonomics, 15*(4), 281–287.

Frederick, E., Howley, E., & Powers, S. (1986). Lower oxygen demands of running in soft-soled shoes. *Research Quarterly for Exercise and Sport, 57*(2), 174–177.

Hamill, J., Palmer, C., & Van Emmerik, R. E. (2012). Coordinative variability and overuse injury. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology, 4*(1), 45.

Hamill, J., van Emmerik, R. E., Heiderscheit, B. C., & Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics, 14*(5), 297–308.

Heiderscheit, B. C., Hamill, J., & van Emmerik, R. E. (2002). Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. *Journal of Applied Biomechanics, 18*(2), 110–121.

Hoerzer, S., Trudeau, M. B., Edwards, W. B., & Nigg, B. M. (2016). Intra-rater reliability of footware-related comfort assessments. *Footwear Science, 8*(3), 155–163.

Hopkins, W. G. (2005). Competitive performance of elite track- and field athletes: Variability and smallest worthwhile enhancements. *Sports Medicine, 9*, 17–20.

Jordan, C., & Bartlett, R. (1995). Pressure distribution and perceived comfort in casual footwear. *Gait & Posture, 3*(4), 215–220.

Kinchington, M. A., Ball, K. A., & Naughton, G. (2011). Effects of footwear on comfort and injury in professional rugby league. *Journal of Sports Sciences, 29*(13), 1407–1415.

Lindorfer, J., Kröll, J., & Schwameder, H. (2019). Comfort assessment of running footwear: Does assessment type affect intersession reliability? *European Journal of Sport Science, 19*, 177–185. doi:10.1080/17461391.2018.1502358.

Luo, G., Stergiou, P., Worobets, J., Nigg, B., & Stefanyshyn, D. (2009). Improved footwear comfort reduces oxygen consumption during running. *Footwear Science, 1*(1), 25–29.

Maiwald, C., Sterzing, T., Mayer, T. A., & Milani, T. L. (2009). Detecting foot-to-ground contact from kinematic data in running. *Footwear Science, 1*(2), 111–118.

Miller, R. H., Meardon, S. A., Derrick, T. R., & Gillette, J. C. (2008). Continuous relative phase variability during an exhaustive run in runners with a history of iliotibial band syndrome. *Journal of Applied Biomechanics, 24*(3), 262–270.

Miller, J. E., Nigg, B. M., Liu, W., Stefanyshyn, D. J., & Nurse, M. A. (2000). Influence of foot, leg and shoe characteristics on subjective comfort. *Foot & Ankle International, 21*(9), 759–767.

Mills, K., Blanch, P., & Vicenzino, B. (2010). Identifying clinically meaningful tools for measuring comfort perception of footwear. *Medicine & Science in Sports & Exercise, 42*(10), 1966–1971. doi:10.1249/MSS.0b013e3181ddac88.

Mills, K., Blanch, P., & Vicenzino, B. (2012). Comfort and midfoot mobility rather than orthosis hardness or contouring influence their immediate effects on lower limb function in patients with anterior knee pain. *Clinical Biomechanics, 27*(2), 202–208.

Morgan, D. W., Martin, P. E., & Krahenbuhl, G. S. (1989). Factors affecting running economy. *Sports Medicine, 7*(5), 310–330.

Mündermann, A., Nigg, B. M., Humble, R. N., & Stefanyshyn, D. J. (2003). Orthotic comfort is related to kinematics, kinetics, and EMG in recreational runners. *Medicine & Science in Sports & Exercise, 35*(10), 1710–1719. doi:10.1249/01.MSS.000089352.47259.CA.

Mündermann, A., Nigg, B. M., Humble, R. N., & Stefanyshyn, D. J. (2004). Consistent immediate effects of foot orthoses on comfort and lower extremity kinematics, kinetics, and muscle activity. *Journal of Applied Biomechanics, 20*(1), 71–84.

Mündermann, A., Nigg, B. M., Stefanyshyn, D. J., & Humble, R. N. (2002). Development of a reliable method to assess footwear comfort during running. *Gait & Posture, 16*(1), 38–45.

Mündermann, A., Stefanyshyn, D. J., & Nigg, B. M. (2001). Relationship between footwear comfort of shoe inserts and anthropometric and sensory factors. *Medicine and Science in Sports and Exercise, 33*(11), 1939–1945.

Needham, R., Naemi, R., & Chockalingam, N. (2014). Quantifying lumbar–pelvis coordination during gait using a modified vector coding technique. *Journal of Biomechanics, 47*(5), 1020–1026.

Nigg, B. M. (2010). *Biomechanics of sport shoes*. Calgary: University of Calgary.

Nigg, B. M., Baltich, J., Hoerzer, S., & Enders, H. (2015). Running shoes and running injuries: Mythbusting and a proposal for two new paradigms: ‘Preferred movement path’ and ‘comfort fit’. *British Journal of Sports Medicine, 49*(20), 1290–1294. doi:10.1136/bjsports-2015-095054.

Nigg, B., Mohr, M., & Nigg, S. R. (2017). Muscle tuning and preferred movement path—a paradigm shift. *Current Issues in Sport Science (CISS), 2*, 1–12.

Nigg, B. M., Stefanyshyn, D., Cole, G., Stergiou, P., & Miller, J. (2003). The effect of material characteristics of shoe soles on muscle activation and energy aspects during running. *Journal of Biomechanics, 36*(4), 569–575.

Nigg, B. M., & Wakeling, J. M. (2001). Impact forces and muscle Tuning: A new paradigm. *Exercise and Sport Sciences Reviews, 29*(1), 37–41.

Nunnemla, A., Keranen, T., & Mikkelsen, L. O. (2007). Factors related to top running speed and economy. *International Journal of Sports Medicine, 28*(8), 655–661. doi:10.1055/s-2007-964896.

Rodrigues, P., Chang, R., TenBroek, T., van Emmerik, R., & Hamill, J. (2015). Evaluating the coupling between foot pronation and tibial internal rotation continuously using vector coding. *Journal of Applied Biomechanics, 31*(2), 88–94. doi:10.1123/jab.2014-0067.

Roy, J. P., & Stefanyshyn, D. J. (2006). Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Medicine & Science in Sports & Exercise, 38*(3), 562–569. doi:10.1249/01.mss.0000193562.22001.e8.

Santos-Concejero, J., Tam, N., Granados, C., Izarzaga, J., Bidaurrazaga-Letona, I., Zabala-Lili, J., & Gil, S. M. (2014). Interaction effects of stride angle and strike pattern on running economy. *International Journal of Sports Medicine, 35*(15), 1118–1123.

Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004). Factors affecting running economy in trained distance runners. *Sports Medicine, 34*(7), 465–485.

Tartaruga, M. P., Briswaller, J., Peyre-Tartaruga, L. A., Avila, A. O., Alberton, C. L., Coertjens, M., … Kruel, L. F. (2012). The relationship between running economy and biomechanical variables in distance runners. *Research Quarterly for Exercise and Sport, 83*(3), 367–375. doi:10.1080/02701391.2012.10599870.

Winter, D. A. (2009). *Biomechanics and motor control of human movement* (4th ed). Hoboken: John Wiley & Sons.