Determinants of footwear perception in running shoes with different compression stiffnesses

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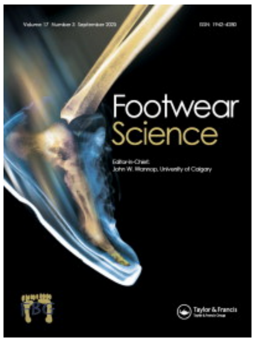
Abstract

Running shoe midsole cushioning is critical in comfort perception and running performance. Optimizing the midsole stiffness could help reduce injury risk and enhance performance by aligning shoe properties with individual runner preferences. Therefore, this study aimed to explore the multifactorial relationships between biomechanical, physiological, sensorimotor, and socio-cultural factors influencing individual perceptions of shoes with varying midsole cushioning stiffnesses. Nineteen participants performed treadmill runs in two shoe conditions with varying midsole stiffness. Biomechanical and metabolic data, as well as subjective assessments of comfort, cushioning, and stability, were collected. The results revealed that stability perception was primarily driven by a socio-cultural factor, stability importance ($\beta = -0.74$, $p < 0.01$), and a biomechanical parameter, step frequency ($\beta = -0.56$, $p = 0.04$), collectively explaining 56% of variance ($p = 0.03$). In contrast, neither cushioning perception nor comfort perception could be significantly predicted by any biomechanical, physiological, sensorimotor or socio-cultural variables ($p = 0.31 - 0.83$). Overall, our findings suggest that parameters across different domains (biomechanical, physiological, sensorimotor, and socio-cultural) may determine the perception of shoe stability in runners. The strong relationships with individual attitudes and biomechanical parameters underscore the need for personalized approaches in running shoe cushioning design. Furthermore, since such attitudes can be shaped, e.g. through marketing initiatives, these findings highlight the importance of a proper alignment between marketing claims and biomechanical findings relating to injury risk and performance improvements through midsole characteristics.



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RESEARCH ARTICLE

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Determinants of footwear perception in running shoes with different compression stiffnesses

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ABSTRACT

Running shoe midsole cushioning is critical in comfort perception and running performance. Optimizing the midsole stiffness could help reduce injury risk and enhance performance by aligning shoe properties with individual runner preferences. Therefore, this study aimed to explore the multifactorial relationships between biomechanical, physiological, sensorimotor, and socio-cultural factors influencing individual perceptions of shoes with varying midsole cushioning stiffnesses. Nineteen participants performed treadmill runs in two shoe conditions with varying midsole stiffness. Biomechanical and metabolic data, as well as subjective assessments of comfort, cushioning, and stability, were collected. The results revealed that stability perception was primarily driven by a socio-cultural factor, stability importance ($\beta = -0.74$, $p<0.01$), and a biomechanical parameter, step frequency ($\beta = -0.56$, $p=0.04$), collectively explaining 56% of variance ($p=0.03$). In contrast, neither cushioning perception nor comfort perception could be significantly predicted by any biomechanical, physiological, sensorimotor or socio-cultural variables ($p=0.31-0.83$). Overall, our findings suggest that parameters across different domains (biomechanical, physiological, sensorimotor, and socio-cultural) may determine the perception of shoe stability in runners. The strong relationships with individual attitudes and biomechanical parameters underscore the need for personalized approaches in running shoe cushioning design. Furthermore, since such attitudes can be shaped, e.g. through marketing initiatives, these findings highlight the importance of a proper alignment between marketing claims and biomechanical findings relating to injury risk and performance improvements through midsole characteristics.

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Footwear; midsole; perception; running economy; biomechanics

Introduction

Distance running has proven benefits for cardiovascular and mental health (Cooney et al., 2013; Hespanhol Junior et al., 2015; Oja et al., 2015). Perceived joy during running is a key factor ensuring persistent involvement in running activities (Clough et al., 1989). Consequently, ensuring that runners perceive their running experience as comfortable, safe, and easy should be a key objective for healthcare systems and footwear manufacturers. The compression of running shoe midsoles has been shown to attenuate loads by redistributing them in time and space (Goonetilleke, 1999), which affects perception (Keshvari et al., 2020; Miller et al., 2000). Therefore, optimizing midsole compression stiffness is a key target in footwear development. However, current research demonstrates critical gaps in understanding how midsole compression stiffness interacts with individual biomechanical and perceptual factors to influence running outcomes.

Impact peak attenuation can indicate a link between objective, biomechanical measures and subjective, perceived cushioning comfort (Keshvari et al., 2020). Additionally, the distribution of peak pressures (e.g. heel peak pressure, ground reaction force loading rate, median power frequency, and impact forces) is associated with comfort perception (Hennig et al., 1996; Milani et al., 1997). However, runners' responses to different levels of midsole compression stiffness and other running shoe design features show substantial inter-subject variability in perceptual variables (Mills et al., 2018; Tay et al., 2017). This variability might be influenced by a complex interplay of biomechanical, physiological, sensorimotor, and socio-cultural factors.

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Biomechanically, it is well established that runners can be very different with respect to their running styles (Van Oeveren et al., 2024). In this study, the authors postulated that spatiotemporal parameters such as duty factor (the ratio of stance time to stride time) and step frequency are sufficient to classify runners into distinct biomechanical profiles ('Stick', 'Bounce', 'Push', 'Hop', and 'Sit'). Building on this framework, examining individual kinematic characteristics provides deeper insight into how individual running mechanics contribute to the perception of midsole systems. For example, differences in foot strike patterns might influence the biomechanical loading of different structures of the lower limbs (Daoud et al., 2012) and change the pressure distribution within the midsole of running shoes. When running barefoot, runners often land on the fore- or midfoot, whereas rearfoot strikers typically rely on the heel's fat pad, which may not be sufficient to absorb impact forces effectively during running. Rearfoot strikers often prefer softer cushioning stiffness in shoe midsoles to compensate for the limited shock-absorbing capacity of the rearfoot structures (Lieberman et al., 2010). This adaptation might help to align the foot strike with the shoe's cushioning capabilities to enhance comfort and reduce impact peaks, especially at slower running speeds (Hasegawa et al., 2007). Meyer et al. (2018) showed that the variability of movement execution can be influenced by footwear comfort, but this relationship is complex. For instance, lower footwear comfort has been associated with reduced kinematic variability in certain aspects of the running motion, particularly in the second half of the swing phase (Meyer et al., 2018). However, this does not necessarily mean that runners change their kinematics in response to comfort; rather, their inherent kinematic patterns may influence how they perceive comfort and stability in different midsole stiffnesses (Hoitz et al., 2020; Sterzing et al., 2013; Trudeau et al., 2019). Specifically, different midsole compression stiffness has been shown to affect ankle joint flexion angles at touchdown (Kersting & Brüggemann, 2006) and the range of motion at knee and ankle joints (Nigg et al., 2012). Understanding these biomechanical factors is crucial for developing footwear that aligns with the diverse needs of runners and enhances their overall running experience and performance (Dinato et al., 2015; Luo et al., 2009).

Physiologically, an increased metabolic cost of transport (COT), the metabolic energy used by the human body to move a certain distance, might be related to a poorer comfort perception in harder shoes (Luo et al., 2009; Worobets et al., 2014). The relationship between cushioning and COT is complex. Cushioning reduces eccentric muscle contractions and soft tissue vibrations during impact attenuation by dissipating mechanical energy through midsole deformation, thereby changing the required physiological work and potentially lowering metabolic cost (Giandolini et al., 2020). This efficiency gain, however, is partially offset by the increased shoe mass, which elevates pendular energy expenditure during leg swing (Tung et al., 2014). Tung et al. showed that a moderate thickness of softer foam cushioning can reduce COT when running shod and unshod on a cushioned treadmill. This suggests that optimizing cushioning stiffness could reduce COT by aligning with the physiological needs of runners. While previous studies have explored the impact of different cushioning materials on COT, there is a need for a deeper understanding of how different foams have evolved over the years (Dinato et al., 2015; Frederick et al., 1986; Worobets et al., 2014). Worobets et al. (2014) compared two different foam types, ethylene vinyl acetate and expanded thermoplastic polyurethane, with regard to their stiffness, resilience, and impact on running performance. However, these studies overlooked the variation in cushioning stiffness within the same material type, which can affect performance (Knopp et al., 2024). Recent work by Denis et al. (2024) reveals a critical trade-off in footwear design: while softer midsoles improved running economy, runners perceived firmer designs as more stable.

Sensorimotor response is another crucial aspect when considering differences between runners and their perception of cushioning systems. The foot, as the only point of contact with the ground, relies on sensory feedback from cutaneous receptors to regulate gait patterns. These receptors provide essential information about pressure, vibration, and sensitivity, which are vital for maintaining balance and adjusting movement during running (Nurse & Nigg, 2001). Therefore, it is necessary to quantify individual plantar foot sensitivity (Mills et al., 2018) to elucidate the dynamics of foot-ground interaction and understand individual comfort perception of cushioning technologies. Variability in sensory feedback can lead to differences in how runners perceive the comfort of cushioning systems. For instance, runners with higher plantar foot sensitivity may be more sensitive to changes in cushioning stiffness, potentially preferring softer or more responsive cushioning to enhance comfort (Nurse & Nigg, 2001). Conversely, runners with reduced sensitivity might not perceive these differences as strongly, leading to varied comfort perceptions among individuals. Understanding how sensory feedback influences gait and comfort perception can help develop more personalized footwear solutions that align with individual sensorimotor needs. This approach could enhance both comfort and performance by optimizing the interaction between the foot and the ground.

Socio-cultural influences, including marketing, peer influences, and cultural beliefs, might shape attitudes and choices towards running shoes and their cushioning stiffness, thereby affecting satisfaction. Individual beliefs have already been shown to influence behaviour towards wearing different shoes. As footwear and identity are linked together, people may build up a resistance towards footwear changes (Branthwaite et al., 2013; Hockey et al., 2013; Nicholls et al., 2018). A study investigating the prevalence and factors associated with outdoor footwear types in a representative inpatient population highlighted how these choices are also influenced by sociodemographic and medical factors (Barwick et al., 2018). However, to the knowledge of the authors, no study has holistically analyzed the impact of marketing, peer influences, and cultural beliefs on footwear design feature perception. Marketing strategies, in particular, can influence consumer preferences by creating brand loyalty and shaping perceptions of what constitutes a 'good' running shoe. Peer influences also play a crucial role, as runners often seek advice from fellow runners or join running communities that share similar preferences and values (Hockey & Allen-Collinson, 2013). Cultural beliefs about health, fitness, and fashion further complicate these choices, as different cultures may prioritize different aspects of footwear design.

Holistic studies that combine objective data and subjective assessments may provide a more comprehensive insight into footwear effects. Understanding this interplay is essential for designing footwear that not only meets functional and clinical needs but also aligns with social preferences. Therefore, analysing the interplay among biomechanical, physiological, sensorimotor, and socio-cultural factors is crucial for comprehending how different runners perceive midsole compression stiffness. This comprehensive insight underscores the challenge of designing footwear that not only meets technical specifications but also adapts to the individual needs of runners to optimize performance and reduce injury risk. Moreover, recognizing the role of these determinants helps in predicting user satisfaction and adherence to running as a physical activity, thus supporting broader public health goals by encouraging a more active lifestyle.

Therefore, this study aimed to explore the multifactorial relationships between biomechanical, physiological, and sensorimotor variables, as well as the role of individual attitudes influencing individual perceptions of shoes with varying midsole cushioning stiffnesses. This work could inform individual-specific footwear design and marketing recommendations to improve runners' satisfaction and participation.

Based on previous literature, we first hypothesized that runners with different running biomechanics would perceive softer and harder shoes differently. More specifically, we hypothesized that runners with more rearfoot-orientated foot strikes would perceive softer shoes as more comfortable, and secondly, runners with longer ground contact times (e.g. higher duty factor and lower step frequency) would perceive harder shoes as more stable. The third hypothesis was that COT influences a runner's preferences for midsole stiffness, expecting that runners would perceive shoes with a lower COT as more favourable across perception domains. Fourth, we hypothesized that runners with greater plantar tactile sensitivity prefer softer midsoles over harder midsoles. Fifth, we hypothesize that runners with positive attitudes and priorities towards softer midsoles will perceive softer midsoles as more positive.

Materials and methods

Participants

Twenty recreational runners, consisting of ten males and ten females (mean ± SD; age: 26.1 ± 3.7 years, height: 171.8 ± 8.9 cm, body mass: 70.4 ± 14.7 kg) with an average running distance of 17.4 ± 13.6 km/week, participated in the study. A recreational runner was defined as an individual running at least once but not more than three times per week for at least six months (Mulvad et al., 2018). To be included in the study, runners must have been free of injury for at least six months; this was controlled using the OSTRC questionnaire, asking for lower limb injuries (Clarsen et al., 2013). The study received ethical approval from the local Research Ethics Committee (ethical approval code 01/24), and all participants signed informed consent forms before participation. The participants were recruited through local running clubs and flyers distributed around the university facilities.

Footwear conditions

Two footwear conditions provided by adidas AG were used in this experiment (Adidas Ultraboost). A softer prototype shoe (ShoeSoft) and a harder control condition (ShoeHard). The conditions were structurally identical in all respects (e.g. UK women's size 5, 5.5, 6 and UK men's size 8, 8.5, 9) except for vertical compression stiffness. ShoeHard weighed 321 grams, and ShoeSoft weighed 273 grams. To equalize the influence of different shoe masses on running biomechanics and COT (Rodrigo-Carranza et al., 2020), 50 grams of small lead strips were taped to the tongue of the shoe upper on the midfoot of each shoe. Mechanical testing was conducted using a mechanical testing system (Instron, Norwood, USA). With a session consisting of 20 consecutive loading and unloading cycles, each cycle compressed at a rate of 4250 N/s until a maximal load of 2000 N was reached, followed by unloading. The stiffness (compliance) and hysteresis (resiliency) of the footwear midsoles were quantified during the 20th loading-unloading cycle, as the maximal load divided by the maximum deformation. Energy loss was represented as the area between the loading-unloading curves. Stiffness of each shoe was calculated as the change in force from the peak force (i.e. 2000 N) to the unloaded state (i.e. 0 N) divided by the difference between maximum deformation to the unloaded state. Then, stiffness and maximum deformation were normalized to the control condition ShoeHard (Table 1).

Data collection

Protocol

A randomized mirrored crossover design was used to investigate the effect of different shoe cushioning stiffnesses on biomechanical, metabolic, and subjective measures. Each participant attended a single 90-minute lab session where they performed six running trials on a flat force-instrumented treadmill (Bertec Corporation, Columbus, Ohio, USA). The protocol included a five-minute individual warm-up followed by a two-minute treadmill familiarisation at a speed of 2.7 m/s. Participants performed two five-minute runs in each of the two footwear conditions (Barrons et al., 2024), in a mirrored order at the same running speed for a total of four runs. During the last minute of each trial, metabolic and biomechanical data were collected to ensure a metabolic steady state. To avoid fatigue effects, participants had a five-minute rest period between trials. Subsequently, participants completed a perception questionnaire upon completing the second trial in each shoe condition.

Table 1. Results from mechanical testing for ShoeSoft and ShoeHard in UK men's size 8.5.

	ShoeSoft	ShoeHard
Shoe mass (before normalisation) (g)	273	321
Rearfoot thickness (mm)	39.8	42.0
Rearfoot stiffness (%)	91.4	100
Rearfoot energy return (%)	82.4	80.8
Rearfoot maximum deformation (%)	109.43	100
Forefoot thickness (mm)	28.9	30.0
Forefoot stiffness (%)	89.87	100
Forefoot maximum deformation (%)	111.3	100
Forefoot energy return (%)	82.8	80.9

Biomechanics

Kinematic data was collected at 200 Hz using an 18-camera motion capture system (Qualisys, Gothenburg, Sweden). The kinematic assessment was based on previous publications (Willwacher et al., 2013), where specifically markers were placed on the left and right anterior superior iliac spines and posterior superior iliac spines. For the thigh, markers were placed on the greater trochanter, lateral femoral epicondyle, and a triad cluster on the lateral aspect of the thigh. Shank markers were placed on the medial and lateral femoral epicondyles, medial and lateral malleoli, and a triad cluster on the lateral aspect of the shank. Shoe-markers were placed on the calcaneus, first and fifth metatarsal heads, and the tip of the second toe. Three-dimensional ground reaction (GRF) force data was collected at 2000 Hz using a force-instrumented treadmill to identify all data points where the vertical GRF component exceeded a threshold value of 50 N, which defined the stance phase.

Perception

Before the start of each measurement, participants were asked to fill out a questionnaire about their injury history (Clarsen et al., 2013), preferences and attitudes regarding running shoe stability, cushioning, ride, and comfort using a 0-100 mm Visual Analog Scale (VAS) (Figure S1). Post-trial, participants evaluated each shoe condition using another VAS that was anchored as follows: cushioning intensity from very hard (0 mm) to very soft (100 mm), stability from very unstable (0 mm) to very stable (100 mm), ride from very difficult (0 mm) to very easy (100 mm), fatigue from very exhausting (0 mm) to very easy (100 mm), and overall comfort from very uncomfortable (0 mm) to very comfortable (100 mm) (Figure S2).

Sensorimotor

Additionally, foot sensitivity was assessed using Semmes-Weinstein monofilaments at specific points (calcaneus, first and fifth metatarsophalangeal joints, and under the big toe), increasing monofilament thickness until sensation was reported (McPoil & Cornwall, 2006). The monofilament with the selected force value is positioned vertically at a 90-degree angle on the test site, and a light force is applied until the monofilament bends slightly without being stroked or slid over the skin. This position with force exerted is maintained for two seconds, after which the participants are asked to indicate whether they feel pressure at any of the corresponding testing points. Each monofilament application is repeated three times for the right foot.

Physiology

Resting oxygen consumption was recorded before the warm-up in a standing position. During each running trial, metabolic data were captured at the last minute using a breath-by-breath method with a metabolic cart (Vyntus, Vynair Medical, Mettawa, USA).

Data analysis

Due to technical problems, only 19 of the original 20 participants were included in the analysis of the data.

Biomechanics

Kinematic and kinetic data were processed and analyzed using a custom-made MATLAB script (The MathWorks, Inc., Natick, MA, USA). Marker trajectories and GRF data were smoothed with a recursive, fourth-order digital Butterworth low-pass filter with a cut-off frequency of 20 Hz (Mai & Willwacher, 2019). A three-dimensional model consisting of five rigid body segments (pelvis, thigh, shank, rearfoot, forefoot) and Cardan angle convention was utilized to calculate joint kinematics (Willwacher et al., 2013). The analysis focused on the stance phase of the right leg. Duty factor was calculated as contact time divided by the sum of contact and flight time (Van Oeveren et al., 2024). Since there were technical issues with the instrumented treadmill, no 3D force data was used except for stance-phase detection.

Perception

Perception data, captured on a 0–100 mm scale, were entered into a CSV spreadsheet.

Sensorimotor

Average sensitivity was quantified by the smallest monofilament thickness stimulus detected at each of the four specified landmarks and was entered into a CSV spreadsheet.

Physiology

Oxygen consumption and carbon dioxide production data from the final minute of each trial were analyzed using a custom MATLAB script. Data points of carbon dioxide and oxygen measurements were filtered for outliers using a Grubbs test, with replacements made by averaging values plus or minus two standard deviations as necessary. Average VO_2 and VCO_2 ($mL{\cdot}min^{-1}{\cdot}kg^{-1}$) were calculated, as well as individualized to the mass-specific cost of transport ($J{\cdot}kg^{-1}{\cdot}m^{-1}$) to body mass and belt velocity as presented by Peronnet and Massicotte (1991), with averages calculated across the two trials. ΔCOT (change in cost of transport) was calculated analogously to the perception deltas, as the difference between ShoeHard and ShoeSoft conditions

Statistical analysis

This study utilized multiple robust linear regression models with an alpha level of 0.05 to examine the relationships between perception delta values (ShoeHard minus ShoeSoft) and a set of biomechanical, physiological, sensorimotor, and socio-cultural factors. Positive delta values indicate a preference for ShoeHard, reflecting a favour towards stiffer midsole properties, while negative values suggest a preference for softer cushioning stiffness; values around zero indicate no perceived difference between the two conditions. All predictor variables were standardized using z-score transformation prior to analysis to ensure comparability of regression coefficients. To reduce dimensionality and address potential multicollinearity, predictors were screened based on pairwise correlations and variance inflation factors (VIF), with all retained predictors exhibiting VIF values below the exclusion threshold of 5. The correlation matrix of the dependent variables reveals significant interrelationships among domains ($|r| > 0.7$) (Figure 2). The final models included three dependent variables (Δcomfort, Δcushioning, and Δstability) and eight predictors (ankle flexion angle at touchdown, duty factor, step frequency, COT in ShoeHard, ΔCOT, average tactile sensitivity, cushioning attitude, and stability importance, Table 2). Robust regression was performed to account for outliers and heteroscedasticity in the small sample ($n = 19$), using iteratively reweighted least squares. This method improves model stability by repeatedly updating the weights assigned to each data point based on their residuals, reducing the influence of those with large errors. The weighting scheme followed Tukey's bisquare function, which uses a smooth curve to progressively downweight extreme residuals while retaining the central structure of the data. The influence of each point decreases as its residual increases, and points with very large residuals receive near-zero weight. This curve is governed by a tuning constant ($k = 4.685$), which balances sensitivity to outliers against robustness. The regression was implemented using custom MATLAB code, and HC3 heteroscedasticity-consistent standard errors were used to provide reliable inference despite non-constant variance and the limited sample size (n = 19). Separate regression models were constructed for each perception delta. Model fit was assessed using adjusted R-squared, root mean squared error (RMSE), and robust F-tests. Residual diagnostics included Q-Q plots for normality, Breusch-Pagan tests for homoscedasticity (all $p > 0.15$), and leverage diagnostics to identify influential data points.

Results

Multiple robust regression models explained 56% of the variance in ΔStability (R^2 = 0.755, adjusted R^2 = 0.560), 14.9% in ΔComfort (R^2 = 0.527, adjusted R^2 = 0.149), and −27.9% in ΔCushioning (R^2 = 0.289, adjusted R^2 = −0.279). Only the model for ΔStability reached statistical significance ($F(8,10)$ = 3.87, $p = 0.024$), whereas the models for ΔComfort ($F(8,10)$ = 1.4, $p = 0.305$) and ΔCushioning ($F(8,10)$ = 0.509, $p = 0.825$) did not (Figure 1). The regression models revealed distinct predictor-perception relationships across biomechanical, physiological, sensorimotor, and socio-cultural domains (Table 3).

Table 2. Discrete parameters as input for the regression analyses.

Biomechanics	Ankle flexion at touchdown, duty factor, step frequency
Physiology	COT ShoeHard, ΔCOT
Sensorimotor	Average tactile sensitivity
Socio-cultural	Stability importance, cushioning attitude,

Biomechanics

For biomechanical factors, step frequency was significantly negatively associated with ΔStability (β = −0.56, 95% CI [−1.1, −0.02], $p = 0.04$), indicating that runners with a higher step frequency perceived the ShoeSoft as more stable compared to ShoeHard. Duty factor showed a trend towards a positive association with ΔStability (β = 0.69, 95% CI [0.042, 1.344], $p = 0.06$), meaning that runners with a greater proportion of stance time perceived the ShoeHard as more stable. In contrast, neither duty factor nor step frequency significantly predicted ΔCushioning ($p = 0.83$ and p = 0.38, respectively) or ΔComfort ($p = 0.20$ and $p = 0.12$, respectively). Ankle flexion at touchdown did not show significant effects on any perception outcome ($p > 0.50$).

Physiology

In physiological measures, COT was not significantly associated with any of the perception deltas: ΔStability (β = 0.06, 95% CI [−0.72, 0.85], $p = 0.86$), ΔComfort (β = 0.05, 95% CI [−0.71, 0.80], $p = 0.89$), and ΔCushioning (β = −0.11, 95% CI [−0.84, 0.62], $p = 0.74$). ΔCOT was also not significantly associated with ΔStability (β = 0.31, 95% CI [−0.20, 0.83], $p = 0.20$,), ΔComfort (β = 0.14, 95% CI [−0.34, 0.61], $p = 0.53$), or ΔCushioning (β = −0.10, 95% CI [−0.75, 0.54], $p = 0.74$).

Sensorimotor

Sensorimotor factors, quantified by average tactile sensitivity, showed a trend-level negative association with ΔStability (β = −0.45, 95% CI [−0.94, 0.04],

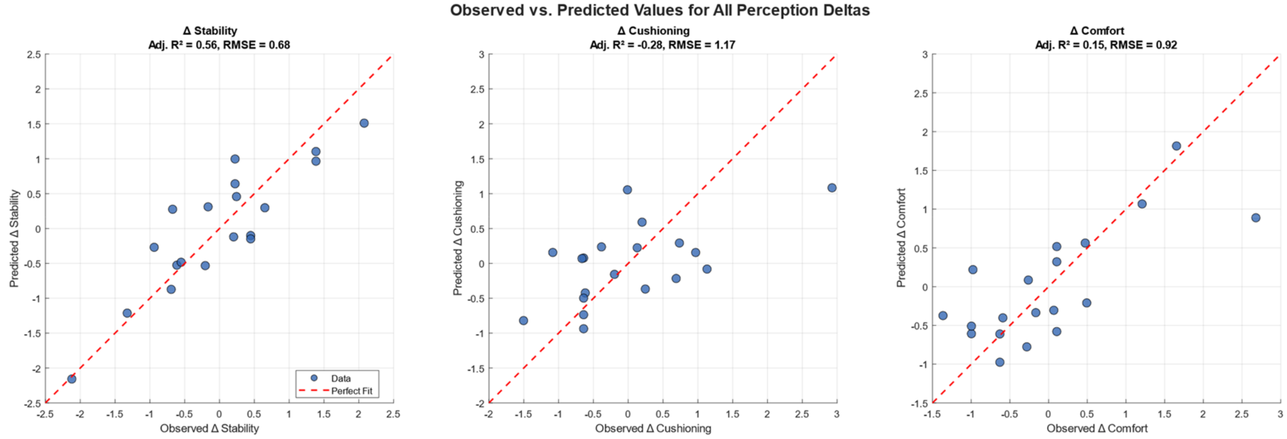

Figure 1. Regression models for multiple robust regression analysis for Δ in perception, including R2 and root mean square errors (RMSE).

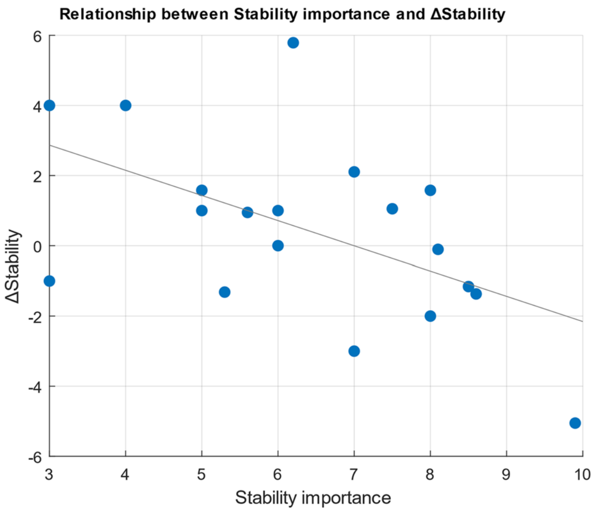

Figure 2. Partial regression plot for stability importance and ΔStability.

Table 3. Coefficient table for the regression analysis predicting ΔStability. The table includes predictor domains, estimates (β), standard errors, t-statistics, and p-values. Significant predictors ($p < 0.05$) are highlighted in bold.

Domain	Predictor	Estimate (β)	Standard Error	t-statistic	*p*-value
Biomechanics	Ankle flexion at touchdown	−0.22	0.33	−0.67	0.519
	Duty factor	0.69	0.33	2.09	0.063
	Step frequency	−0.56	0.24	−2.30	**0.044**
Physiology	COT ShoeHard	0.06	0.35	0.18	0.864
	ΔCOT	0.31	0.23	1.37	0.202
Sensorimotor	Average tactile sensitivity	−0.45	0.22	−2.03	0.069
Socio-cultural	Cushioning attitude	−0.28	0.29	−0.94	0.368
	Stability importance	−0.74	0.21	−3.62	**0.005**

$p=0.07$). Runners with more sensitive feet perceived harder shoes as more stable. However, there was no significant association for sensitivity with ΔComfort (β = −0.26, 95% CI [−0.83, 0.31], $p=0.34$) or ΔCushioning (β = −0.07, 95% CI [−0.89, 0.75], $p=0.86$).

Socio-cultural

Among socio-cultural variables, stability importance was significantly negatively associated with ΔStability (β = −0.74, 95% CI [−1.20, −0.29], $p=0.005$), indicating that higher subjective importance of stability is associated with higher perceived stability in ShoeSoft. However, stability importance was neither significant for ΔComfort (β = −0.46, 95% CI [−1.08, 0.15], $p=0.13$), nor for ΔCushioning (β=0.05, 95% CI [−0.72, 0.81], $p=0.89$). Cushioning attitude was not significantly associated with any outcome: ΔStability (β = −0.28, 95% CI [−0.94, 0.38], $p=0.37$), ΔComfort (β = −0.08, 95% CI [−0.84, 0.68], $p=0.83$), or ΔCushioning (β = −0.22, 95% CI [−1.32, 0.89], $p=0.68$).

Discussion

The purpose of this study was to explore the multifactorial relationships between biomechanical, physiological, sensorimotor, and socio-cultural domains influencing individual perceptions of shoes with varying midsole cushioning stiffnesses. Our most prominent finding is that stability perception was primarily driven by socio-cultural and biomechanical domains.

Biomechanically, the analysis revealed correlations between running kinematics and shoe perception. Runners with higher step frequencies perceived softer midsoles as more stable, potentially from interactions between frequency-driven loading patterns and midsole deformation dynamics. Elevated step frequencies reduce ground contact time, potentially amplifying vertical leg stiffness (Farley & González, 1996), which could intensify contrasts in midsole compression-recoil behaviour. During rapid loading phases, softer materials compress more readily but exhibit slower rebound kinetics, while firmer midsoles resist deformation with faster elastic return (Shorten, 1993). This stiffness-dependent energy storage disparity becomes perceptually salient at higher cadences, where shorter contact phases limit force dissipation time, as demonstrated in a study linking cadence to leg stiffness modulation (Anderson et al., 2022). Conversely, the trend towards greater stability perception for firmer midsoles in runners with higher duty factors may reflect prolonged stance phases allowing firmer materials to maintain structural integrity under sustained loads. This aligns with findings by Kulmala et al. (2018), who reported that less leg stiffness is required when running in firmer shoes, potentially enhancing stability through reduced reliance on muscular compensation during the stance phase. In addition to previous findings by Lieberman et al. (2010) that highlight differences in impact forces based on foot strike patterns, in our study, the foot angle at touchdown was not related to any perception deltas. Therefore, our first hypothesis needs to be rejected.

Our second hypothesis linking longer ground contact times to firmer midsole stability preferences is partially supported, but points out a critical nuance. Our study uniquely identifies step frequency, rather than stance duration alone, as the critical biomechanical determinant of stability perception. This finding shifts the focus towards spatiotemporal gait parameters as primary drivers of footwear perception and aligns with previous research indicating that running biomechanics may influence how individuals perceive and interact with different shoe designs (Dinato et al., 2015). The observed relationships between stride characteristics and shoe perception underscore the importance of considering individual running styles when designing or prescribing running shoes.

Physiologically, our results indicate that neither COT nor changes in COT were associated with runners' perceptions of stability, comfort, or cushioning across different midsole stiffnesses. This finding does not support our third hypothesis, which posited that shoes yielding a lower COT would be perceived more favourably. While earlier studies have shown that optimized cushioning can reduce COT by minimizing eccentric muscle work during impact (Luo et al., 2009; Tung et al., 2014), and by different foam materials and constructions (Dinato et al., 2015; Worobets et al., 2014), our data suggest that COT does not directly translate to subjective footwear perception. Recent work by Denis et al. (2024) further supports this dissociation, demonstrating that although softer midsoles may optimize running economy, runners often perceive firmer midsoles as more stable. These findings highlight that, within the context of midsole stiffness, metabolic COT and subjective comfort or stability perception are not necessarily aligned, and that runners may prioritize biomechanical cues over marginal metabolic advantages when evaluating footwear.

Sensorimotor parameters, quantified by average tactile sensitivity, were not significantly associated; however showed a trending negative association with ΔStability ($\beta = -0.45$, $p = 0.07$). Runners with lower average tactile sensitivity values (more sensitive) perceived ShoeHard as more stable. There was no significant association with ΔComfort ($\beta = -0.26$, $p = 0.34$) or ΔCushioning ($\beta = -0.07$, $p = 0.86$). These findings partially contradict our hypothesis that runners with heightened plantar tactile sensitivity would perceive softer midsoles more favourably. While Mills et al. (2018) showed that runners who preferred cushioned shoes were generally more sensitive to mechanical pain at specific plantar areas, our results suggest that average tactile thresholds may only predict stability, but not comfort perception of moderate midsole stiffness variations. The absence of sensitivity effects contrasts with Keshvari et al. (2020), who reported regional plantar differences in cushioning perception, implying that average sensitivity metrics may lack discriminatory power. This discrepancy could arise from insufficient variability in participant sensitivity. Furthermore, Meyer et al. (2018) showed that runners alleviate discomfort through kinematic adjustments rather than relying on tactile acuity. These results underscore that tactile sensitivity, while critical for balance (Hennig & Sterzing, 2009), is secondary to determining footwear perception.

Our fourth hypothesis postulated that runners with greater plantar tactile sensitivity would perceive softer midsoles differently. This hypothesis can not be accepted since we did not find any significant associations between tactile sensitivity and perception deltas. The focus of footwear design should therefore be shifted towards other domains.

The socio-cultural findings from this study provide valuable insights into the relationships between runners' attitudes towards shoe features and their perceptions. Our results indicate that runners who place greater subjective importance on stability tend to perceive softer midsoles as more stable, a finding that may initially seem counterintuitive but suggests a complex interplay between expectations and perceptual experience. In contrast, attitudes towards cushioning did not significantly predict perceptions of stability, cushioning or comfort ($p = 0.37$–0.83), indicating that preconceived notions about cushioning may have less immediate impact on acute perceptual responses in controlled settings. A runner's attitude and personal importance might be related to more internal experiences, such as running or injury history, or externally shaped influence from marketing. These results highlight the complex interplay between individual preferences, beliefs, and subjective experiences of running shoe properties. Our findings on the importance of stability and cushioning attitude in shoe perception align with key factors identified in recent literature. In their systematic review, Fife et al. (2023) identified 40 factors influencing road runners' shoe selection, grouped into five categories: subjective, shoe-specific characteristics, market features, peer evaluation, and runner characteristics. Our study's results particularly resonate with the subjective and shoe-specific characteristics categories. The strong influence of stability importance on stability perception in our study underscores the significance of preconceived notions in shaping runners' experiences. This also aligns with the 'comfort filter' paradigm proposed by Nigg et al. (2015), which suggests that individual preferences and expectations play a crucial role in how runners perceive shoe comfort. Furthermore, Fife et al. (2023) noted that comfort, stability and cushioning were among the most frequently cited factors influencing footwear selection, supporting our observations. Our finding that runners who ranked stability as important perceived softer shoes as more stable adds nuance to the understanding of stability in running shoes. This counterintuitive result challenges common assumptions and aligns with recent research questioning traditional paradigms in running shoe design (Nigg et al., 2020). Our results regarding the influence of runners' attitudes and priorities on shoe perception support the emphasis on individual characteristics in shoe selection. While our study did not directly address peer evaluation and market features, Fife et al. (2023) highlighted their significance in shoe selection. These aspects could provide context for some of our findings, as the preferences we observed might be influenced by broader trends in the running community or marketing strategies. Therefore, our fifth hypothesis can be accepted, as individual beliefs and attitudes towards cushioning systems were shown to influence participants' perceptions.

In conclusion, our findings on the relationships between runners' attitudes and shoe perceptions complement and extend the current understanding of running shoe selection and perception. They underscore the complex, multifaceted nature of this process, aligning with recent research that emphasizes individual variability and attitudes towards design features, such as cushioning stiffness, and the need for personalized approaches in shoe design and recommendation (Mills et al., 2018; Nigg et al., 2015).

The analysis of perception deltas reveals significant interrelationships among various aspects of shoe comfort and performance. Notably, strong correlations ($|r| > 0.7$) were found between comfort and ride perceptions, comfort and fatigue perception, and ride and fatigue perception, indicating that runners who find a shoe comfortable also perceive it as providing a better ride and experiencing less fatigue. This underscores the interconnected nature of these perceptions, suggesting that improvements in one determinant may enhance others. Additionally, the significant relationship between stability and comfort perceptions indicates that a runner's sense of stability contributes to their overall comfort experience. The correlation between stability and fatigue suggests that enhanced perceived stability may lead to reduced fatigue during running. A trend was observed between cushioning and comfort perception, hinting at a potential link that merits further investigation. Overall, these findings highlight the importance of considering the holistic nature of shoe perceptions in design and evaluation, as improvements in one aspect, such as comfort or stability, could positively influence other perceptual parameters (Hébert-Losier et al., 2024).

This study has several strengths that contribute to its value in understanding runner-shoe interactions. The comprehensive approach, integrating biomechanical, physiological, sensorimotor, and socio-cultural aspects, provides a holistic view of factors influencing shoe perception. The use of mass-normalized shoes with controlled differences in midsole stiffness allows for systematic comparisons of this specific property. The inclusion of both objective measurements and subjective perceptions enhances our understanding of the complex relationship between shoe properties and runner experiences. However, there are limitations to consider when interpreting the results. The sample size of 19 participants (ten females and nine males) is relatively small, particularly for concluding sex-specific or performance-related effects. The absence of 3D force data limits our ability to fully characterize biomechanical interactions between runners and shoes, as information on ground reaction forces and impact loading rates could provide valuable insights (Hasegawa et al., 2007). The study's focus on immediate perceptions of recreational runners during short running bouts in a controlled laboratory environment and running speed may not fully capture the complexities of long-term shoe use in real-world conditions (Hoogkamer et al., 2017).

Future research should expand our understanding in several key areas. Long-term studies should investigate how runners adapt to different shoe types over extended periods and how these adaptations affect perception and injury risk, as comfort was also shown to influence pain and injury risk (Mündermann et al., 2001). Conducting research in natural running environments would provide insights into how various shoe features influence perceptions and performance in day-to-day conditions. Integrative studies exploring the complex interactions among biomechanical, physiological, sensorimotor, and socio-cultural factors are crucial for a comprehensive understanding of runner preferences and experiences. Longitudinal injury risk assessments could evaluate how individual shoe preferences and perceptions correlate with long-term injury rates and running performance. Finally, investigating the effectiveness of personalized shoe recommendations based on individual biomechanical, physiological, and perceptual profiles could lead to more tailored and effective shoe selection processes. These research directions aim to provide a more comprehensive and applicable understanding of runner-shoe interactions, potentially leading to improved shoe designs, more effective personalized recommendations, and reduced injury risk.

Conclusion

This study reveals the multifactorial relationships between biomechanical, physiological, sensorimotor, and socio-cultural factors in runners' perceptions of shoes with varying midsole cushioning stiffnesses. Key findings include correlations between running kinematics and shoe perception, a trend between COT and stability perception, the role of tactile sensitivity in stability perception, and the influence of individual importance on shoe stability perceptions. These results highlight that individual attitudes play a key role in how runners perceive and interact with different shoe properties, underscoring the need for personalized approaches in running shoe design and selection that consider the unique characteristics and attitudes of each runner. Externally shaped attitudes, such as marketing influence, should therefore align with proper scientific knowledge, which external stakeholders should consider to improve runners' satisfaction and participation.

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