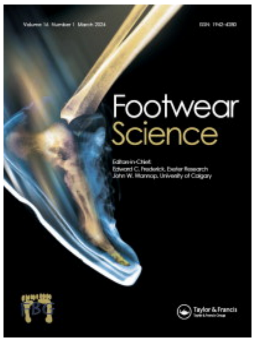

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RESEARCH ARTICLE

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Biomechanics and subjective measures of recreational male runners in three shoes running outdoors: a randomised crossover study

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ABSTRACT

We compared biomechanical and subjective data from outdoor running in: habitual (OWN), Saucony Endorphin Racer 2 minimal (FLAT) and Nike Vaporfly 4% (VP4) shoes. We also explored relationships between comfort measures and the collected data. Eighteen male recreational runners ran three 1.5-km trials outdoors, once per shoe. The first 1.1 km was run at a self-selected comfortable (slower) speed, and last 400 m at perceived 5-km race pace (faster). A GPS-enabled smartwatch, 15-m Optojump system, high-speed camera and tibial accelerometer collected biomechanical data. Subjective data on comfort, shoe properties and overall running experience were collected using visual analogue scales (VAS) and rankings. Cadence, leg stiffness and vertical stiffness were greater in FLAT than both OWN and VP4 at the slower speed (*trivial* to *small* ES). At both speeds, footstrike angles were smaller in FLAT (*small* to *large* ES), while propulsion phase was shorter in VP4 (*moderate* to *large* ES). FLAT was ranked as the least comfortable at the slower speed and most likely to cause injury, whereas OWN as the most comfortable and least likely to cause injury. Comfort was not significantly different at the faster speed between shoes. Comfort measures were more strongly correlated to subjective than biomechanical data. The two experimental shoes generally had non-significant or *small* effects on running biomechanics versus OWN. As VP4 are more like traditional than minimal shoes, these were perceived as more comfortable. Running speed appeared to affect subjective measures. Speed should be considered when prescribing and selecting shoes.

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Comfort; minimalist shoes; running; super shoes

1. Introduction

The majority of the running community are recreational runners (Besomi et al., 2018), with comfort, performance and injury prevention considerations motivating their shoe choice (Dhillon et al., 2020). Minimalist shoes are defined as 'footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height and the absence of motion control and stability devices' (Esculier et al., 2015). The concept behind minimalist shoes is to mimic barefoot running biomechanics whilst protecting the foot from the external environment. Minimalist shoes 'promote our natural barefoot running style' (Davis, 2014) and are proposed to potentially prevent common running-related injuries (i.e., most common injuries are at the knee), with the caveat that their design increases loading at the foot and ankle albeit reducing the loads at the knees (Bermon, 2021). Indeed, running biomechanics in minimal shoes differs to conventional shoes and typically results in a lower footstrike angle (i.e., less rearfoot) and higher cadence (Barcellona et al., 2017). Furthermore, the lighter mass of these shoes overall decreases oxygen consumption (Fuller et al., 2015) with potential performance benefits. Racing shoes are typically lighter for this reason. Therefore, minimal shoes might appeal to recreational runners from an injury prevention and performance perspective.

At the opposite end of the spectrum, technologically advanced shoes have become popular since 2017 when Nike released the Vaporfly 4% (VP4). The VP4 contained novel technologies claiming to return energy, which ultimately led to the emergence of shoes with advanced footwear technology (AFT). Although there is no consensus definition (Hébert-Losier & Pamment, 2023), shoes with AFT typically contain a thicker midsole than previously available racing shoes that is constructed of polyether block amide (PEBA) elastomer foam instead of the traditionally used ethylene-vinyl acetate (EVA) (Burns & Tam, 2020). PEBA contains greater energy-return properties than EVA (Bermon, 2021; Muniz-Pardos et al., 2022) and is lighter, meaning it is possible to have a thicker midsole with a

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negligible increase in shoe mass. A curved full-length stiff plate is integrated into the midsole, which increases the longitudinal bending stiffness (Burns & Tam, 2020) and is proposed to reduce the energetic cost of running via reductions in the mechanical energy lost at the metatarsophalangeal joints (Venturini & Giallauria, 2022) and reductions in plantarflexion velocities (Hoogkamer et al., 2019; Ortega et al., 2021). Although the VP4 is reported to reduce energy cost by up to 4% on average in high-calibre (Hoogkamer et al., 2018) and recreational (Hébert-Losier, Finlayson, Driller, et al., 2022) runners compared to other shoes, individual responses are noted, particularly in recreational runners (Hébert-Losier, Finlayson, Driller, et al., 2022). Running in the VP4 has also been associated with longer flight times, lower ankle ranges of motion and lower cadences (Barnes & Kilding, 2019; Hébert-Losier, Finlayson, Driller, et al., 2022) that could increase knee loading. A recent paper reported lesser running economy benefits of AFT shoes at slower speeds (Joubert et al., 2023), suggesting that recreational runners may benefit less from AFT shoes than elite. On the other hand, recreational runners are used to running races in heavier traditional shoes, and transitioning to AFT shoes can reduce distal mass and benefit running economy. The potential performance benefits of AFT shoes may appeal to recreational runners, particularly those with racing or performance goals. AFT shoes are more similar to conventional shoes than minimal ones in several regards (e.g., heel-to-toe drop, stack height, minimalist index rating; Hébert-Losier, Finlayson, Lamb, et al., 2022), and could be easier to transition towards and a more comfortable option for runners seeking performance enhancements than minimal shoes.

Comfort is a key factor for runners when purchasing shoes (Dhillon et al., 2020), with many aspects influencing comfort (Menz & Bonanno, 2021). Shoe features can affect shoe comfort ratings, with forefoot and heel cushioning, shoe stability and forefoot flexibility found to play an important role in overall running shoe comfort assessment (Bishop et al., 2020). The comfort filter paradigm suggests that runners select shoes that are the most comfortable and doing so automatically reduces their injury risk (Nigg et al., 2015), despite the absence of evidence to support this theory (Agresta et al., 2022). Overall, the factors contributing to comfort in recreational runners remain largely unexplored and primarily studied in laboratories (Fife et al., 2023). There are limited studies assessing shoe comfort running outdoors in a more ecologically valid environment.

Therefore, our aims were to compare biomechanical and subjective measures of male recreational runners running outdoors in three different shoes: Nike Vaporfly 4% (VP4), the original AFT shoe; Saucony Endorphin Racer 2, an old generation minimalist lightweight racing flat without carbon-fibre plate (FLAT); and runners' habitual running shoes (OWN). The testing was planned at two different speeds given that VP4 and FLAT are designed for racing. A secondary aim was to examine possible relationships between comfort measures and the collected data (subjective and biomechanical) using exploratory analysis.

2. Materials and methods

2.1. Sample size

Sample size calculations were based on prior work identifying a *moderate* effect size (ES) difference ($f = 0.29$) in baseline visual analogue scale (VAS) comfort ratings between VP4 and FLAT (Hébert-Losier, Finlayson, Driller, et al., 2022). A minimal sample size of 17 runners was required to detect this ES difference in comfort between shoes accounting for three repeated measures (assuming 0.60 correlation and sphericity) using repeated measures ANOVA (within factors) at a 5% significance level and 80% power based on G*Power 3.1.9.7 computations.

2.2. Participants

Eighteen male recreational runners participated (Table 1). To be included, runners needed to be free from injury for at least three months, run regularly (minimum once per week) for at least six months, and have a personal best 5 km time between 20 and 30 min in the past year (Hébert-Losier, Finlayson, Driller, et al., 2022; Honert et al., 2020). Participants signed an informed consent document that outlined the benefits and risks involved (e.g., delayed onset muscle soreness or injury due to running in unfamiliar shoes). The Human Research Ethics Committee [HREC(Health)2020#83] approved the experiment, which adhered to the Declaration of Helsinki.

2.3. Protocol

A randomised crossover study design was used to investigate the effect of shoe on biomechanical and subjective outcomes (Figure 1). Participants attended one 90-min session that involved running 1.5 km in three shoes: OWN, own habitual running shoe; FLAT, Saucony Endorphin Racer 2 racing flat; and VP4, Nike Vaporfly 4% (Table 1). Participants selected their OWN shoes knowing they were required to run 1.5 km outside on asphalt at a comfortable and 5 km race or tempo pace. All participants were rearfoot strikers in their own shoes except for one who was a midfoot striker based on footstrike angles collected during trials (Altman & Davis, 2012).

After providing informed consent, the characteristics of participants (age, height, mass, leg length, running

Table 1. Characteristics of participants ($n = 18$) and shoes worn by participants.

Participants	Males		
Age (y)	31.2 ± 10.5		
Height (cm)	180.2 ± 6.0		
Mass (kg)	81.6 ± 10.0		
Leg length (mm)†	912.1 ± 39.8		
Running experience (years)	11.2 ± 8.1		
5 km personal best time (min)	23.1 ± 2.1		
Weekly training (km)	20.0 ± 12		
Own shoe size (US sizing)	10.6 ± 1.0		
Shoes$	**OWN**	**FLAT**	**VP4**
Mass (g)	$308 \pm 42^{F,V}$	$153 \pm 8^{O,V}$	$211 \pm 12^{O,F}$
Stack height (mm)	24.6 ± 7.2^{F}	$13.0 \pm 0^{O,V}$	31.0 ± 0^{F}
Heel-to-toe drop (mm)	11.2 ± 5.7^{F}	$1.0 \pm 0^{O,V}$	7.0 ± 0^{F}
Minimalist index (%)‡	28 ± 15^{F}	$88 \pm 0^{O,V}$	48 ± 0^{F}
Price (NZD)	156 ± 49^{V}	190 ± 0	$380 \pm 0^{O,F}$

Data are mean ± standard deviation.
†Greater trochanter to ground distance in a standing position barefoot.
$Data from right shoes only (size: US 8.5–12).
‡Minimalist index range: 0% (lowest) to 100% (highest) degree of minimalism.
^{O,F,V}Significant difference during post-hoc paired *t*-test comparisons ($p \leq 0.05$) vs. OWN, FLAT, and VP4, respectively.
FLAT, Saucony Endorphin Racer 2 road racing flat; OWN, runners own habitual running shoes; VP4, Nike Vaporfly 4%.

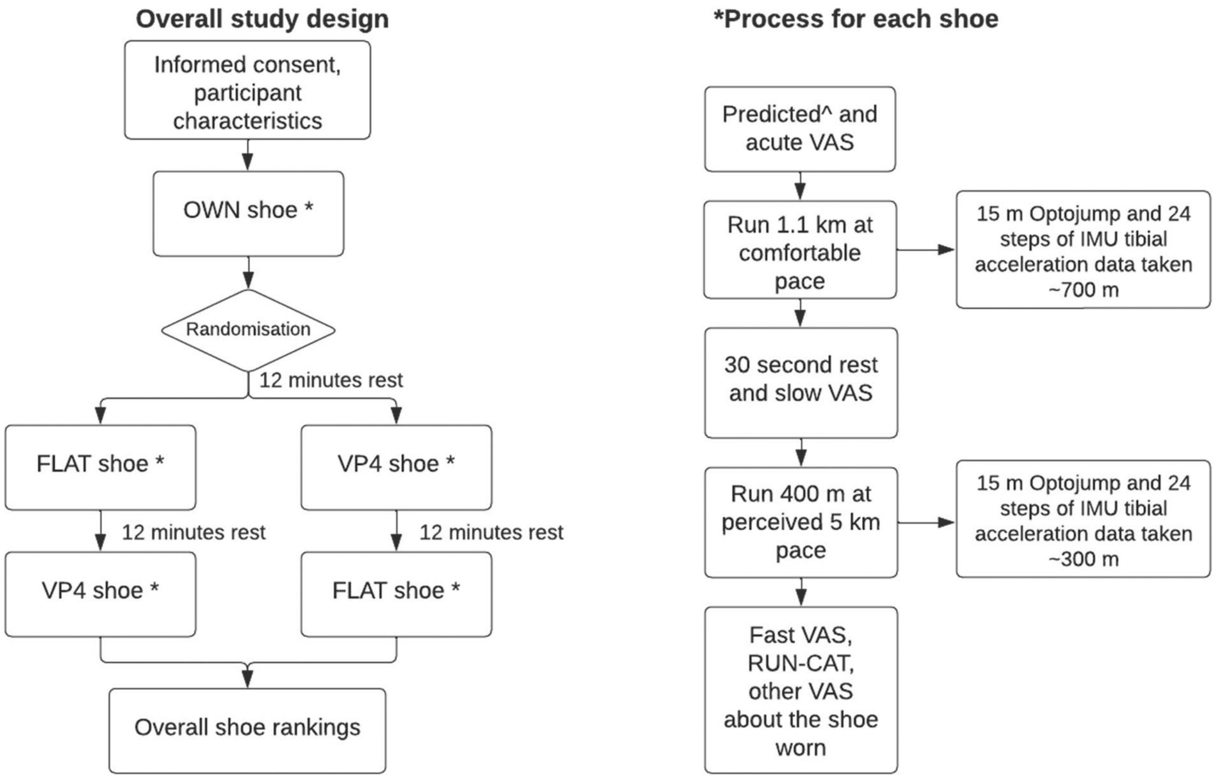

Figure 1. Overall study design (left diagram) and experimental process for each shoe (right diagram). ^FLAT and VP4 only. *Abbreviations.* FLAT, Saucony Endorphin Racer 2 racing flat. IMU, inertial measurement unit. OWN, own habitual running shoe. RUN-CAT, running shoe comfort assessment tool. VAS, visual analogue scale. VP4, Nike Vaporfly 4%.

experience and training level) and their OWN shoes (size, mass, cost, stack height, forefoot height, heel-to-toe drop and reasons for purchasing their shoe) were recorded. Participants trialled the various available sizes of the two experimental shoes to ensure proper fit. The minimalist index of all shoes worn as part of the study was calculated using a valid and reliable tool (Esculier et al., 2015), where 100% represents the highest degree of minimalism and 0% the lowest. Of note, the experimental shoes were spray-painted black to obscure their brand and model and minimise their potential to influence subjective measures.

All running trials were conducted outside around a flat concrete 740 m loop. Participants were first required to run 1.1 km at a self-selected comfortable pace sustainable for 30 min (∼1.5 loops). After a 30 s standing rest, participants ran 400 m at a faster pace as if they were doing a tempo run or 5 km race. The 1.1 km distance was chosen to measure the running shoe comfort assessment tool (RUN-CAT) (Bishop et al., 2020). A faster speed was also examined, given that the VP4 and FLAT are designed for racing. Participants ran the first of the three running trials in their OWN shoes to act as baseline, followed by the VP4 and FLAT in a random order (Figure 1).

2.4. Data collection

2.4.1. Biomechanical measures

During the experimental trials, participants wore a Garmin 245 Music watch (Garmin Ltd., Olathe, Kansas) that monitored their 1.1 km and 400 m running times, and notified them when to start and stop running. Participants ran through 15 m of an optical measurement system (Optojump modular system, Microgate, Bolzano, Italy) 700 m into the 1.1 km trial and 300 m into the 400 m trial. The Optojump system measured speed (m/s), cadence (steps per minute), step length (cm), flight time (ms), contact time (ms) and propulsive phase (%) at a sampling rate of 1000 Hz, where propulsive phase represents the time from heel lifting to toe-off as a percentage of contact time. A levelled iPad Pro 11 sampling at 240 frames per second was positioned on a 30 cm stand, 5 m to the left-hand side of participants in the middle of the 15-m Optojump system. Videos were used to extract footstrike angles (°) using the SiliconCoach Live (The Tarn Group, Dunedin, NZ) video analysis software. In addition, participants wore two IMeasureU blue trident inertial measurement units (Vicon Motion Systems Ltd., Oxford, UK) to capture tibial acceleration (Van den Berghe et al., 2019). The units were placed on the medial tibia just above the medial malleolus and secured using the manufacturer's straps and athletic tape. Each unit has a tri-axial accelerometer with a range of ± 200 g and 1600 Hz sampling rate.

2.4.2. Subjective measures

Several subjective measures were collected pre- and post-running trials, which included a range of 0–100 mm VAS (supplementary material). All comfort VAS endpoints were 'Not comfortable at all' and 'Most comfortable imaginable'. Before putting on the VP4 and FLAT shoes, participants completed a VAS (predicted VAS) on how comfortable they thought the shoes would be based on observing and holding them. For the three shoes, participants completed a pre-run, slow-run and fast-run VAS. The pre-run VAS was completed before the running trials with participants wearing the shoes and permitted to walk and jog around as they would if selecting a shoe in store (acute VAS). The slow-run and fast-run VAS were completed immediately after the 1.1 km and 400 m trials, respectively. After the 1.5 km trials, participants completed a series of other VAS measures to rate their perceptions of the shoe properties and overall running experience (supplementary material). The midpoint of the VAS for shoe properties reflected ideal, and included heel cushioning, forefoot cushioning, forefoot flexibility, shoe stability, shoe stiffness, technical features and shoe weight. Traditional VAS anchor points were used for overall running experience, which included pleasure/displeasure, easiness/hardness, overall performance and injury risk, where the midpoint reflected a neutral response and endpoints reflected the two extremes. At the end of the three running trials, participants were asked to rank the three shoes based on perceived comfort (most to least), performance (best to worst) and injury risk (lowest to highest). Participants were also asked if they knew the make and model of the experimental shoes.

2.5. Data processing

2.5.1. Biomechanical measures

The 15-m Optojump data were averaged across the minimum number of recorded steps common across participants and speads, with was eight steps. Vertical stiffness (k_{vert}) and leg stiffness (k_{leg}) in kN/m were modelled using the spatiotemporal data from the Optojump and leg length measurements using the following equations (Morin et al., 2005):

$$k_{\text{vert}} = F_{\max} \times \Delta y_c{}^{-1}$$

$$k_{\text{lg}} = F_{\max} \times \Delta L^{-1}$$

$$F_{\max} = mg \times \frac{\pi}{2} \times \left(\frac{t_f}{t_c} + 1\right)$$

$$\Delta y_c = \frac{F_{\max} \times t_c^2}{m \times \pi^2} + g\frac{t_c^2}{8}$$

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y_c$$

where m is the mass of participants, g is gravitational acceleration constant (9.81 m/s^2), t_f is flight time (s), t_c is contact time (s), $F_{\max}$ is the modelled maximal force, Δy_c is the modelled centre of mass displacement, ΔL is the peak displacement of the leg spring, L is leg length (greater trochanter to ground distance in a standing position barefoot) and v is running speed (m/s).

The duty factor (*DF*) was also calculated using the Optojump metrics using the following calculations (Alexander & Jayes, 1980; Minetti, 1998).

$$\text{DF} = \frac{\text{SF} \times t_c}{2} \times 100\%$$

$$\text{SF} = 1/\left(\frac{1}{t_f + t_c}\right)$$

where SF is stride frequency.

The raw IMU data were filtered using a double-pass fourth order 60 Hz Butterworth filter (Johnson et al., 2020) applied using RStudio® (version 2022.12.0 + 353) with R (version 4.2.22). The resultant tibial acceleration was then calculated as $\sqrt{(x^2 + y^2 + z^2)}$. Ten seconds of data were averaged (25 to 35 steps per participant) to provide a resultant tibial acceleration measure in vicinity to the 15-m Optojump placement (i.e., 700 m into the 1.1 km trial and 300 m into the 400 m trial).

2.5.2. Subjective measures

The VAS ratings (0–100 mm) were extracted from all VAS scores. The four RUN-CAT related VAS (heel cushioning, forefoot cushioning, flexibility and stability scores) were used to calculate the RUN-CAT score using the following equation (Bishop et al., 2020):

$$\begin{aligned}\text{RUN-CAT} = \; & ((100 - \text{ABS}(50 \\ & - \text{Heel cushioning}) * 2) * 0.175) \\ & + ((100 - \text{ABS}(50 \\ & - \text{Forefoot cushioning}) * 2) * 0.311) \\ & + ((100 - \text{ABS}(50 - \text{Flexibility}) * 2) * 0.247) \\ & + ((100 - \text{ABS}(50 - \text{Stability}) * 2) * 0.277)\end{aligned}$$

where 0 represents the least ideal and 100 the most ideal comfort.

2.6. Statistical analysis

R was used to graph, visualise and explore the data. Repeated measures analysis of variance (RM ANOVA) was used to identify any significant difference in biomechanical and subjective outcomes between shoes, and post-hoc paired t-tests for pairwise comparisons. Cohen's d ES for paired samples were extracted using an average variance, as were their 95% confidence intervals (CI). ES were defined as *small*, *moderate* and *large* when reaching 0.20, 0.50 and 0.80, respectively, and *trivial* when less than 0.20 (Cohen, 1992). Effects were deemed *unclear* when the 95% CI overlapped the threshold for small positive and negative ($d \pm 0.20$). The Friedman test was used to analyse the ranking data and Goodness-of-Fit in post-hoc tests to determine which rankings significantly differed between shoes. Repeated measures correlation (rmcorr R package) (Bakdash & Marusich, 2017) and 95% CI were used to investigate possible relationships between comfort and biomechanical or subjective measures. For scales where 50 mm represents ideal, data were rescaled before exploratory analysis so that 0 mm indicates not ideal, and 100 mm represents most ideal. Given the exploratory nature of this analysis and number of correlations examined, *moderate* ($|r| \geq 0.30$) and *large* ($|r| \geq 0.50$) correlations reaching statistical significance were deemed to reflect potentially meaningful relationships worth exploring in future research (Cohen, 1992). Significance level was set at $p \leq 0.05$ for all analysis.

3. Results

3.1. Biomechanical measures

Biomechanical measures for each shoe at the two different speeds are reported in Table 2, and ES differences with 95% CI are provided as supplementary material (Table S1). There were no significant differences in speed between shoes, except within the 15-m Optojump section when running at the slower speed. In this 15-m section, runners ran faster in FLAT (ES 0.37, *small*) and VP4 (ES 0.28, *small*) than OWN. The FLAT also demonstrated a greater cadence (OWN ES 0.35, *small*; VP4 ES 0.28, *small*), k_{vert} (OWN ES 0.34, *small*; VP4 ES 0.21, *small*) and k_{leg} (OWN ES 0.19, *trivial*; VP4 ES 0.15 *trivial*) at the slower speed, as well as lower footstrike angles at both speeds than the two other shoes (ES 0.47–0.89, *small* to *large*). In addition, FLAT exhibited a smaller duty factor than OWN at the slower speed (ES 0.37, *small*). The only other significant biomechanical difference was seen for the propulsion phase, where VP4 had a significantly shorter propulsion phase at both speeds than OWN and FLAT (ES 0.53–1.18, *moderate* to *large*).

3.2. Subjective measures

3.2.1. Comfort VAS

Subjective measures for each shoe are reported in Table 3 and ES differences with their 95% CI in the supplementary material (Table S2). FLAT had a lower acute comfort compared with OWN (ES 1.20, *large*) and VP4 (ES 0.77, *moderate*). FLAT also had lower scores for slow speed comfort compared to the two other shoes (OWN ES 1.08, *large*; VP4 ES 0.68, *small*). There were no significant differences between shoes for predicted or fast speed comfort.

3.2.2. Shoe properties VAS

Shoe significantly influenced all shoe properties VAS scores, except for shoe stability. Post-hoc comparisons indicated OWN had a significantly higher (more ideal) RUN-CAT than VP4 (ES 0.63, *moderate*) and FLAT (ES 0.95, *large*), with no significant difference detected between the latter. Heel cushioning scores significantly differed between all three shoes (ES 1.22–2.60, *large*), with VP4 exhibiting the highest (too much cushioning) and FLAT the lowest (too little cushioning) mean score. FLAT had significantly lower forefoot cushioning and shoe weight scores than OWN (ES 0.87 and 1.88, respectively, *large*) and VP4 (ES 1.07and 0.81, respectively, *large*); whereas VP4 had significantly lower forefoot flexibility, and higher shoe stiffness and technical features scores than OWN (ES 1.00, 1.44 and 1.23, respectively, *large*) and FLAT (ES 1.35, 1.34 and 1.63, respectively, *large*).

3.2.3. Overall running experience VAS

Runners perceived a lower risk of injury in OWN than VP4 (ES 0.82, *large*) and FLAT (ES 1.27, *large*). No other significant differences were detected.

Table 2. Variables (mean ± standard deviation) collected from the 1.1 km trial at a self-selected comfortable pace (slower) and a 400 m trial at a perceived 5 km pace (faster) ran by participants ($n = 18$).

Variable	Distance	OWN	FLAT	VP4	RM ANOVA (p value)
Overall speed (m/s)	1.1 km	3.57 ± 0.30	3.62 ± 0.35	3.65 ± 0.40	0.447
	400 m	4.18 ± 0.35	4.09 ± 0.36	4.15 ± 0.38	0.071
Optojump measurements					
Speed (m/s)	1.1 km	**3.66 ± 0.33^{V,F}**	**3.80 ± 0.38^{O}**	**3.78 ± 0.42^{O}**	**0.010**
	400 m	4.30 ± 0.36	4.29 ± 0.46	4.34 ± 0.40	0.650
Cadence (steps/minute)	1.1 km	**168.0 ± 7.5^{F}**	**171.1 ± 8.8^{O,V}**	**168.8 ± 8.5^{F}**	**0.005**
	400 m	174.6 ± 8.8	176.2 ± 10.1	174.7 ± 9.1	0.080
Step length (cm)	1.1 km	130.9 ± 11.9	133.2 ± 11.2	134.5 ± 14.4	0.101
	400 m	148.1 ± 11.8	146.1 ± 14.4	149.3 ± 12.4	0.301
Flight time (s)	1.1 km	0.093 ± 0.019	0.097 ± 0.017	0.097 ± 0.021	0.133
	400 m	0.109 ± 0.016	0.107 ± 0.020	0.111 ± 0.018	0.415
Contact time (s)	1.1 km	**0.265 ± 0.021^{F}**	**0.254 ± 0.022^{O}**	0.259 ± 0.023	**0.001**
	400 m	0.236 ± 0.018	0.234 ± 0.022	0.234 ± 0.019	0.650
Propulsive phase (%)	1.1 km	**45.3 ± 4.1^{V}**	**46.6 ± 3.7^{V}**	**43.1 ± 3.9^{O,F}**	**<0.001**
	400 m	**45.7 ± 3.5^{V}**	**47.2 ± 4.0^{V}**	**42.6 ± 3.8^{O,F}**	**<0.001**
k_{vert} (kN/m)	1.1 km	**27.7 ± 3.5^{F}**	**29.2 ± 4.3^{O,V}**	**28.3 ± 3.6^{F}**	**<0.001**
	400 m	31.5 ± 4.1	32.2 ± 4.3	31.8 ± 3.9	0.208
k_{leg} (kN/m)	1.1 km	**12.3 ± 2.7^{F}**	**12.9 ± 2.9^{O,V}**	**12.4 ± 2.6^{F}**	**0.019**
	400 m	12.8 ± 2.9	13.2 ± 2.8	12.9 ± 2.8	0.250
Duty factor (%)	1.1 km	**37.1 ± 2.5^{F}**	**36.1 ± 2.4^{O}**	36.4 ± 2.8	**0.026**
	400 m	34.3 ± 2.1	34.3 ± 2.7	34.0 ± 2.3	0.575
2D camera data					
Footstrike angle (°)	1.1 km	**15.6 ± 6.4^{F}**	**12.4 ± 4.6^{O,V}**	**15.6 ± 6.2^{F}**	**0.003**
	400 m	**15.5 ± 5.8^{F}**	**12.2 ± 5.5^{O,V}**	**16.9 ± 5.1^{F}**	**<0.001**
IMU sensor data					
TRA (g)a	1.1 km	17.3 ± 3.4	19.0 ± 3.3	18.6 ± 4.2	0.134
	400 m	21.1 ± 4.4	22.2 ± 2.8	20.7 ± 3.7	0.421

$^{F,\ O,\ V}$Significant difference ($p \leq 0.05$) vs. FLAT, OWN and VP4 during post-hoc comparisons, respectively. Significant differences ($p \leq 0.05$) are in bold.
[a]Missing data from 4 participants.
2D, two-dimensional; FLAT, Saucony Endorphin Racer 2 road racing flat; IMU, inertial measurement unit; k_{leg}, leg stiffness; k_{vert}, vertical stiffness; OWN, runners own habitual running shoes; RM ANOVA, repeated measures analysis of variance; TRA, tibial resultant acceleration; VP4, Nike Vaporfly 4%.

Table 3. Visual analogue scale (0–100 mm scale, mean ± standard deviation) scores on comfort, shoe properties, and overall running experience of participants ($n = 18$).

Characteristics	OWN	FLAT	VP4	RM ANOVA (p value)
Comfort VAS				
Predicted comfort	–	34.3 ± 21.8	43.5 ± 20.1	0.136
Acute comfort	**66.2 ± 16.7^{F}**	**42.9 ± 21.7^{O,V}**	**60.1 ± 23.0 ^{F}**	**0.003**
Slow speed comfort	**65.2 ± 14.9^{F}**	**42.8 ± 24.4^{O,V}**	**59.4 ± 24.3^{F}**	**0.003**
Fast speed comfort	64.7 ± 16.8	51.3 ± 23.1	57.4 ± 25.7	0.149
Shoe properties VAS				
Heel cushioning*	**48.8 ± 14.3^{F,V}**	**25.6 ± 14.9^{O,V}**	**68.4 ± 17.8^{O,F}**	**<0.001**
Forefoot cushioning*	**45.4 ± 11.0^{F}**	**31.5 ± 19.9^{O,V}**	**52.9 ± 20.1^{F}**	**<0.001**
Forefoot flexibility*	**53.4 ± 14.4^{V}**	**58.4 ± 14.9^{V}**	**38.4 ± 14.5^{O,F}**	**<0.001**
Shoe stability*	46.4 ± 11.7	38.3 ± 16.7	43.4 ± 17.4	0.310
RUN-CAT **	**81.3 ± 10.8^{V,F}**	**64.2 ± 23.1^{O}**	**70.8 ± 19.4^{O}**	**0.031**
Shoe stiffness*	**39.4 ± 14.1^{V}**	**37.8 ± 18.2^{V}**	**58.1 ± 11.7^{O,F}**	**<0.001**
Technical features*	**38.0 ± 13.0$^{V,\ b}$**	**34.3 ± 11.0^{V}**	**55.5 ± 15.4$^{O,\ F}$**	**<0.001**
Shoe weight*	**58.7 ± 9.7$^{F,\ b}$**	**41.7 ± 8.9$^{O,\ V}$**	**50.9 ± 12.9^{F}**	**<0.001**
Overall running experience VAS				
Pleasure/displeasure	59.1 ± 15.7^{b}	40.0 ± 25.3	52.1 ± 26.6	0.068
Easier/harder	55.9 ± 14.0^{b}	44.4 ± 22.7	50.8 ± 23.1	0.237
Performance (worse/improved)	49.4 ± 9.7^{b}	47.6 ± 19.5	52.8 ± 23.5	0.740
Injury risk (lower/higher)	**46.4 ± 20.0$^{F,\ V,\ b}$**	**70.1 ± 16.4^{O}**	**60.2 ± 17.7^{O}**	**0.002**

^{F,O,V}Significant difference during post-hoc comparisons ($p \leq 0.05$) vs. FLAT, OWN and VP4, respectively. Significant differences ($p \leq 0.05$) are in bold.
^{b}Missing data from 1 participant.
*Midpoint (50 mm) represents ideal, 0 mm indicates an absence of the property and 100 mm indicates too much of a property.
**RUN-CAT weighted average of four preceding properties, where 100 represents ideal.
FLAT, Saucony Endorphin Racer 2 road racing flat; OWN, runners own habitual running shoes; RUN-CAT, running shoe comfort assessment tool; VAS, visual analogue scale; VP4, Nike Vaporfly 4%.

Table 4. Ranking of shoes by participants ($n = 18$) values are count (percentage %).

Shoe	Rank 1 (most preferred)	Rank 2	Rank 3 (least preferred)	Friedman (p value)
Comfort at slow speed				**0.011**
Own	**10 (55.6%)**	7 (38.9%)	**1 (5.6%)**	
Flat	**1 (5.6%)**	7 (38.9%)	**10 (55.6%)**	
VP4	**7 (38.9%)**	4 (22.2%)	**7 (38.9%)**	
Comfort at fast speed				0.607
Own	3 (16.7%)	12 (66.7%)	3 (16.7%)	
Flat	5 (27.8%)	1 (5.6%)	7 (38.9%)	
VP4	10 (55.6%)	5 (27.8%)	8 (44.4%)	
Race performance				0.678
Own	6 (33.3%)	9 (50%)	3 (16.7%)	
Flat	5 (27.8%)	6 (33.3%)	7 (38.9%)	
VP4	7 (38.9%)	3 (16.7%)	8 (44.4%)	
Lowest injury risk				**<0.001**
Own	**14 (77.8%)**	**4 (22.2%)**	**0 (0%)**	
Flat	**1 (5.6%)**	**2 (11.1%)**	**15 (83.3%)**	
VP4	**3 (16.7%)**	**12 (66.7%)**	**3 (16.7%)**	

Notes. Significant differences ($p \leq 0.05$) in rankings using Freidman and Goodness-of-Fit in post-hoc tests are in bold.
FLAT, Saucony Endorphin Racer 2 road racing flat; OWN, runners own habitual running shoes; VP4, Nike Vaporfly 4%.

3.2.4. Rankings

The overall shoe rankings are reported in Table 4. In general, OWN was ranked more frequently as the most comfortable shoe at the slow speed, and FLAT as the least comfortable. Runners more frequently ranked OWN as the shoe with the perceived lowest injury risk, and FLAT with the highest. There were no other significant differences in rankings.

3.3. Exploratory analysis

The findings from the exploratory analysis of repeated measures correlations between the comfort measures and the subjective and biomechanical ones are shown in Table 5 and their CI in supplementary material (Table S3). Overall, the subjective measures (comfort, shoe properties and overall running experience) were more often meaningfully correlated (i.e., significant and *moderate* or *large*) to comfort than the biomechanical metrics. Ratings of pleasure/displeasure were significantly correlated to all comfort measures ($r = 0.481$–0.776), as were perceptions of running difficulty (easier/harder, $r = 0.402$–0.757). The measures that were meaningfully correlated to acute comfort (heel cushioning, forefoot cushioning, shoe stiffness, perceived injury risk) were also meaningfully correlated to slow speed comfort, fast speed comfort and RUN-CAT, but strength of correlations changed. Slow speed comfort, fast speed comfort and RUN-CAT were also meaningfully correlated to shoe stability. Shoe stability and performance VAS were meaningfully correlated to fast speed comfort and RUN-CAT only ($r = 0.468$). RUN-CAT scores were significantly correlated to all three comfort VAS scores, but the most strongly to fast speed comfort ($r = 0.720$).

Table 5. Repeated measures correlations between comfort measures and subjective and biomechanical measures of data from 18 participants.

	Predicted comfort	Acute comfort	Slow speed comfort	Fast speed comfort	RUN-CAT
Comfort VAS					
Predicted comfort	1.000	–	–	–	–
Acute comfort	0.376	1.000	–	–	–
Slow speed comfort	0.270	**0.679**	1.000	–	–
Fast speed comfort	0.369	**0.534**	**0.715**	1.000	–
Shoe properties VAS					
Heel cushioning*	−0.003	**0.400**	**0.451**	**0.567**	**0.832**
Forefoot cushioning*	−0.075	**0.371**	**0.669**	**0.636**	**0.901**
Forefoot flexibility*	0.386	0.264	0.322	**0.595**	**0.438**
Stability*	−0.160	0.284	**0.524**	**0.391**	**0.791**
RUN-CAT**	0.004	**0.436**	**0.673**	**0.720**	1.000
Shoe stiffness*	0.315	**0.352**	**0.429**	**0.540**	**0.431**
Technical features*	0.003	−0.164	−0.063	0.014	0.184
Shoe weight*	0.053	0.158	0.006	0.153	0.095
Overall running experience VAS					
Pleasure/displeasure	**0.481**	**0.534**	**0.647**	**0.776**	**0.714**
Easier/harder	**0.511**	**0.402**	**0.560**	**0.757**	**0.582**
Performance (worse/improved)	0.367	0.175	0.171	**0.468**	**0.400**
Injury risk (lower/higher)	0.014	**−0.567**	**−0.564**	**−0.396**	**−0.579**
Biomechanical measures					
Overall speed (1.1 km)	0.154	0.070	0.026	0.095	0.157
Overall speed (400 m)	0.045	0.131	0.078	0.189	0.260
Cadence	**−0.494**	−0.236	−0.117	−0.160	−0.127
Step length	0.157	0.202	0.053	**0.353**	0.011
Flight time	0.109	0.137	0.066	0.275	0.043
Contact time	0.228	0.018	−0.013	−0.146	0.043
Propulsive phase	−0.128	−0.307	−0.217	−0.095	−0.099
k_{vert}	−0.436	−0.135	−0.103	0.026	−0.123
k_{leg}	−0.308	−0.159	−0.055	−0.098	−0.066
Duty factor	0.157	0.027	0.117	−0.145	0.029
Footstrike angle	0.018	0.237	0.162	0.108	0.223
TRA	−0.462	−0.243	−0.214	−0.235	0.054

Notes. Significant correlations ($p \leq 0.05$) that are *moderate* ($|r| \geq 0.30$) or *large* ($|r| \geq 0.50$) are deemed meaningful and shown in bold.
*Original scores where the midpoint (50 mm) represents ideal were rescaled before exploratory analysis so that 0 mm indicates 'not ideal' and 100 mm presents 'most ideal'.
**RUN-CAT weighted average of four preceding properties, where 0 represents not ideal and 100 represents most ideal.
k_{leg}, leg stiffness; k_{vert}, vertical stiffness; RUN-CAT, running shoe comfort assessment tool; TRA, tibial resultant acceleration; VAS, visual analogue scale.

4. Discussion

Our study adds to the growing body of knowledge surrounding the effects of minimalist and AFT shoes on running biomechanics and subjective measures, including comfort and perceptions. It is the first study to examine footwear comfort running outdoors in a more ecologically valid environment that compares a minimalist shoe, a shoe with AFT and runners' habitual shoes. Our findings align with previous research reporting changes in biomechanics in minimalist (Squadrone et al., 2015) and AFT shoes (Hoogkamer et al., 2019), as well as differences in perceived comfort in these shoes (Dinato et al., 2015). The significant biomechanical differences between shoes were generally of *small* ES, except for propulsion phase and footstrike angle measures where *moderate* and *large* ES differences were found. In contrast, the significant differences in comfort and subjective ratings were *large*. Running speed appeared to affect comfort levels and shoe rankings, an aspect not often addressed in research. Furthermore, our results reinforce the subjective nature of comfort as indicated by the lack of association between biomechanical measures and overall comfort.

4.1. Biomechanical measures

Both experimental shoes affected the biomechanics of our recreational runners. Notably, FLAT involved higher cadence and lower footstrike angles (i.e., less rearfoot) than the two other shoe conditions, which is consistent with previous research on minimalist shoes (Barcellona et al., 2017; Nigg et al., 2020; Perkins et al., 2014). Although the changes in biomechanics were generally of *small* magnitude with potentially limited impact on load distribution, the minimal cushioning of shoes would increase loading at the foot and ankle (Bermon, 2021), warranting caution in transitioning too quickly to more minimalist shoes from more (maximalist) traditional shoes to minimise injury risk to these structures. We also noted *moderate* to *large* differences in the propulsive phase between shoes, with the VP4 having a shorter propulsive phase than FLAT and OWN. This finding could be due to the proposed teeter-totter effect associated with the curved stiff carbon fibre plate and forefoot geometry of the VP4 (Nigg et al., 2021), leading to a quicker transition from midstance to toe-off. Our findings overall suggest that running in VP4 is more like running in traditional shoes than minimalist ones, suggesting that the adaptation period to novel shoes may be quicker for AFT than minimalist shoes for recreational runners used to traditional shoes. Nonetheless, care is still advised in the process of integrating AFT shoes in training and racing given that foot injuries can still occur while wearing carbon fibre plated shoes (Tenforde et al., 2023). There is currently a lack of research on how these shoes interact with the foot and affect foot mechanics.

4.2. Comfort and speed

Runners rated the comfort of FLAT shoes as lower than OWN and VP4 acutely and at the slower running speed, whereas differences in comfort were not significant at the faster speed. These findings suggest that running speed affect comfort ratings. This link between shoe comfort and speed has been proposed elsewhere (Blazey et al., 2021) despite the limited research on this topic. It could be that runners focus less on footwear comfort when running at race pace and experience greater physiological discomfort.

Comfort is a key factor in running shoe selection (Dhillon et al., 2020; Fife et al., 2023). In-store, runners typically decide to try shoes based on their look and feel in their hands. This initial perception was encapsulated in our predicted VAS score. It is worth noting that this predicted VAS score did not significantly relate to the acute, slow, or fast comfort VAS scores once runners had worn the shoes. The acute comfort reflects the initial perception of runners in-store when trying on shoes. This acute comfort was largely related to slow and fast speed comfort ratings, although they correspondingly explained only 29–46% of the variance in acute comfort. Hence, it is important that runners have the opportunity to run in shoes more than a few steps prior to purchase to properly assess running comfort. Similarly, although comfort ratings at the slow and fast speeds were largely correlated ($r = 0.715$), the correlation was not perfect. Furthermore, shoe stability and performance VAS scores were meaningfully related to fast, but not slow, speed comfort. Together, these results highlight the potential for speed to affect comfort and the importance of trialling shoes at multiple running speeds. The different rankings of shoes at the slower and faster speeds also reinforce this implication. Indeed, FLAT was most frequently ranked as the least comfortable at the slow speed, but shoe rankings were more evenly spread across the three shoes at the fast speed and for race performance. These results reflect how footwear habits (i.e., most recreational runners wear more traditional running shoes) together with beliefs that greater cushioning is protective against injury influence footwear perceptions with regards to injury risk, and how shoe preference is individual in nature (Kong & Bagdon, 2010).

4.3. Shoe properties VAS

A noteworthy observation is the lower variation (i.e., smaller SD values) in the comfort VAS and RUN-CAT scores for OWN than the two experimental shoes because runners were familiar with running in their shoes. The greater variance in VAS and RUN-CAT scores in VP4 and FLAT reflect the individualised preferences and responses of runners to novel shoes (Kong & Bagdon, 2010). The RUN-CAT is a composite score that reflects deviations from ideal comfort. RUN-CAT scores were similar between FLAT and VP4, but for opposite reasons. The two experimental shoes are at opposite ends of the spectrum with regards to several shoe characteristics, which was reflected in the VAS ratings of runners with regards to shoe properties. For example, the VP4 heel cushioning score implies that it was perceived as too cushioned at the heel despite having close to ideal forefoot cushioning. In contrast, the FLAT was perceived as having too little cushioning at both the heel and forefoot. Additionally, runners perceived the VP4 as having too little forefoot flexibility compared to FLAT and OWN likely due to the carbon plate increasing longitudinal bending stiffness (Nigg et al., 2020) that was unfamiliar to most runners. Although the tool was designed to assess comfort at the slower speed (i.e., 1.1 km self-selected pace), we found RUN-CAT scores were more strongly correlated with comfort at the faster ($r = 0.720$) than the slower ($r = 0.673$) speed. This observation suggests the RUN-CAT is valid for assessing overall shoe comfort at faster running speeds outdoors, particularly when involving shoes designed for racing. However, the results might also reflect the fact that the RUN-CAT data were collected immediately at the end of the 1.5 km trials, after participants had just completed their fast effort in shoes. More importantly, the RUN-CAT is potentially mainly linked with running shoe habits of runners, from where cushioning are the driving factors of the RUN-CAT scores. A comprehensive study on this topic is needed to confirm RUN-CAT relevance for habitual minimal shoe wearers and differences with change in speed.

4.4. Injury prevention

Injury prevention is an important consideration to runners when selecting shoes (Dhillon et al., 2020). Most runners (83.3%) ranked the FLAT as the shoe with the perceived highest injury risk. This finding may be due to lower familiarity to minimalist shoes like the FLAT in recreational runners and beliefs that more cushioning can protect against injury, while shoes like the VP4 are more similar in construct to traditional running shoes and have a greater amount of cushioning. Plantar sensitivity is lowered in cushioned shoes (Francis & Schofield, 2020), with minimal shoe running increasing loads on the intrinsic foot muscles (Johnson et al., 2016). It could be that runners were more sensitive to mechanical-induced pain sensations (Mills et al., 2018) and not adapted from a neuromuscular perspective to minimal shoe running, hence the perception of greater injury risk. We do acknowledge, however, that these results may have differed in a population of habitual minimal shoe wearers. The comfort filter paradigm (Nigg et al., 2015) posits that runners intuitively select the most comfortable shoe using their own comfort filter, which will match their function and movements and reduce injury risk. Despite the lack of convincing evidence to support a comfort–injury link (Agresta et al., 2022), in the current context, it is likely that comfort would be a relatively good indicator of runners' neuromuscular and metatarsal readiness for minimal shoe running. Transitioning to novel shoes can increase the risk of injury in the short term due to changes in biomechanics and loading. Caution is needed during transitioning to any type of novel shoes, with the minimum time and training volume needed for accommodation and adaptation remaining relatively unknown and likely to be individual and shoe dependent (Tenforde et al., 2023; Warne & Gruber, 2017).

4.5. Exploratory analysis

The results of the exploratory analysis relating comfort to the collected data suggest that subjective VAS measures during running are more strongly related to comfort ratings than biomechanical measures. This finding re-emphasises the subjective nature of comfort (Menz & Bonanno, 2021) and potentially limited relationship between comfort and running biomechanics, as reported elsewhere (Dinato et al., 2015). With the obtained results, we hypothesise that footwear habits influence the perception of comfort in the sense that the closer runners are to their habitual shoes, the more the shoe is perceived as comfortable. The pleasure or displeasure experienced by runners when wearing a particular shoe was strongly correlated with all measures of comfort. This finding is not entirely surprising, given that people are likely to enjoy their running experience more if they feel comfortable in their shoes. Similarly, the more comfortable the participants were in a shoe, running felt 'easier' on the perceived effort scale. This finding goes in the same direction as the comfort filter paradigm (Nigg et al., 2015). The correlation of effort (easiness-hardness) and feeling (pleasure-displeasure) to comfort ratings was *large* and significant at both the slow and fast speed, although the magnitude of the relationship was stronger when running fast. The increased strength of the correlation when running faster suggests that the perception of comfort may change depending on the speed at which one is running, or again reflect the temporal proximity of the ratings. Future research could investigate the use of comfort tools at multiple running speeds to determine their relative interchangeability.

4.6. Strengths and limitations

This study has limitations to acknowledge. Participants self-selected their running speed for all trials. Although there were no significant differences in the overall speed for both the slow and fast running segments, differences in speed were significant in the 15-m Optojump section during slow running when the biomechanical measures were collected. This difference in speed over the 15-m may have impacted running biomechanics; however, the largest difference in average speed (0.13 m/s) was of a *small* ES magnitude and less than 5% between shoes, which is the usual threshold applied when prescribing a set speed in running research (Bergstra et al., 2015; Queen et al., 2006).

Our relatively small sample size is another limitation, particularly in interpreting results from our exploratory analysis as some findings could be due to chance. For this reason, we set a more conservative threshold ($|r| \geq 0.30$) and encourage future research to confirm the presence of a relationship. Our sample contained only male recreational runners that were primarily rearfoot strikers in their own habitual running shoes. Consequently, the generalisation to females and other cohorts of runners is constrained, and their perceptions of comfort influenced by their footwear habits.

Our study also only looked at one AFT shoe and minimalist shoe model. The VP4 model is typically known as being the first AFT shoe. Now, many running shoe companies have several shoes incorporating AFT with slightly different shoe properties (Joubert & Jones, 2022). Hence, although generalisation of findings to other AFT shoes is not ensured, previous research examining a range of AFT shoes indicate little biomechanical differences between shoes (Joubert & Jones, 2022) and strong correlations between subjective rankings and running economy rankings in shoes.

Strengths of our study include conducting the study outdoors, which enhances the ecological validity of findings. Most running training and racing are conducted outdoors, hence the importance of assessing shoe-related performances in such environments. Previous studies (Benson et al., 2020; García-Pérez et al., 2014; Milner et al., 2020; Van Hooren et al., 2020) have demonstrated differences in running biomechanics between laboratory and outdoor running. Our resultant tibial acceleration values are relatively high, but these values are consistent with studies comparing laboratory to outdoor running (García-Pérez et al., 2014; Milner et al., 2020). Another strength of our study is the focus on recreational runners who represent the largest proportion of runners and who have historically not been considered in AFT shoe research. Furthermore, our study examined both subjective and biomechanical measures, which are useful in investigating the multifactorial nature of shoe comfort.

5. Conclusion

The two novel shoes generally had non-significant or *small* effects on runners' biomechanics versus their OWN shoes, except for footstrike angles in FLAT and propulsive phase in VP4 where effects were *moderate* to *large*. Participants were more comfortable in their habitual shoes and VP4, potentially preferring VP4 more than FLAT because the former are more like traditional running shoes. The FLAT minimalist shoes were perceived as the least comfortable and having a higher injury risk. Running speed appeared to affect comfort levels and shoe preferences, which should be considered in research and in shoe prescription to align with the running demands and goals of individuals. Our results re-emphasise the subjective nature of comfort and individualised shoe preference, as well as the general lack of association between comfort and biomechanical measures.

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Disclosure statement

Blaise Dubois and Jean-François Esculier are employed by The Running Clinic, a continuing education organisation which translates scientific evidence to healthcare professionals and the public. Kim Hébert-Losier is a speaker for The Running Clinic.

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Data availability statement

The data that support the findings of this study are openly available in OSF at http://doi.org/10.17605/OSF.IO/A64N5 (Hébert-Losier, 2023).

Authors' contributions

Conceptualisation: KHL. Methodology: KHL, HK, SJF, BD, JFE, CMB. Data Curation: KHL, HK, SJF. Formal Analysis: KHL, HK. Investigation: KHL, SF, CMB, CM. Project Administration: KHL. Resources: KHL. Supervision: KHL. Visualisation: KHL, HK. Writing – Original Draft: KHL, HK. Writing – Review & Editing: KHL, HK, SJF, BD, JFE, CMB.

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