Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjsp20

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To cite this article: Kim Hébert-Losier, Steven J. Finlayson, Peter F. Lamb, Matthew W. Driller, Ivana Hanzlíková, Blaise Dubois, Jean-Francois Esculier & Christopher Martyn Beaven (2022): Kinematics of recreational male runners in "super", minimalist and habitual shoes, Journal of Sports Sciences, DOI: 10.1080/02640414.2022.2081767

To link to this article: https://doi.org/10.1080/02640414.2022.2081767

JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2022.2081767

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SPORTS MEDICINE AND BIOMECHANICS

Kinematics of recreational male runners in "super", minimalist and habitual shoes

Kim Hébert-Losier[a,b], Steven J. Finlayson[a], Peter F. Lamb[c], Matthew W. Driller[d], Ivana Hanzlíková[e], Blaise Dubois[b], Jean-Francois Esculier[b,f] and Christopher Martyn Beaven[a]

[a]Division of Health, Engineering, Computing and Science, Te Huataki Waiora School of Health, University of Waikato, Tauranga, New Zealand; [b]Research & Development, The Running Clinic, Lac Beauport, Québec, Canada; [c]School of Physical Education, Sport and Exercise Sciences, University of Otago, Dunedin, New Zealand; [d]Sport and Exercise Science, School of Allied Health, Human Services and Sport, La Trobe University, Melbourne, Victoria, Australia; [e]Department of Physiotherapy, Faculty of Physical Culture, Palacký University Olomouc, Olomouc, Czech Republic; [f]Department of Physical Therapy, University of British Columbia, Vancouver, British Columbia, Canada

ABSTRACT

We conducted an exploratory analysis to compare running kinematics of 16 male recreational runners wearing Nike Vaporfly 4% (VP4), Saucony Endorphin racing flat (FLAT), and their habitual (OWN) footwear. We also explored potential relationships between kinematic and physiological changes. Runners (age: 33 ± 12 y, ¥ O_{2peak}: 55.2 ± 4.3 $ml \cdot kg^{-1} \cdot min^{-1}$) attended 3 sessions after completing an ¥ O_{2peak} test in which sagittal plane 3D kinematics at submaximal running speeds (60%, 70% and 80% υ ¥ O_{2peak}) were collected alongside economy measures. Kinematics were compared using notched boxplots, and between-shoe kinematic differences were plotted against between-shoe economy differences. Across intensities, VP4 involved longer flight times (6.7 to 10.0 ms) and lower stance hip range of motion (~3°), and greater vertical pelvis displacement than FLAT (~0.4 cm). Peak dorsiflexion angles (~2°), ankle range of motion (1.0° to 3.9°), and plantarflexion velocities (11.3 to 89.0 $deg \cdot sec^{-1}$) were greatest in FLAT and lowest in VP4. Foot-ground angles were smaller in FLAT (2.5° to 3.6°). Select kinematic variables were *moderately* related to economy, with higher step frequencies and longer step lengths in VP4 and FLAT associated with improved economy versus OWN. Footwear changes from OWN altered running kinematics. The most pronounced differences were observed in ankle, spatiotemporal, and foot-ground angle variables.

ARTICLE HISTORY
Accepted 13 May 2022

KEYWORDS
Biomechanics; gait; footwear; minimalist

1. Introduction

For several years, shoe mass was one of the few footwear features consistently linked with running performance and economy improvements (Franz et al., 2012; Fuller et al., 2015; Hoogkamer et al., 2016), with ~0.7% to 1.1% lower energetic costs of running seen for every 100 g of lighter footwear mass (Franz et al., 2012; Hoogkamer et al., 2016). Minimal footwear has become an active area of research and interest to the running community (Rothschild, 2012) due to their lightweight characteristics and resemblance to barefoot running (Lieberman et al., 2010). Compared to more traditional running shoes, running in minimal footwear generally promotes a more forefoot strike pattern, smaller foot-ground angle, greater knee flexion at ground contact, and smaller knee flexion angles during stance (Perkins et al., 2014).

More recently, improvements in world record running times are attributed to technological rather than physiological factors (Muniz-Pardos et al., 2021) as evidenced by the use of "super shoes". The Nike Vaporfly 4% (VP4) was the first "super shoe" introduced to the market. This shoe was lighter than similar marathon racing shoes; had a thick midsole constructed from Pebax® (polyether block amide) foam with substantial energy return characteristics; and contained a curved carbon fibre plate that increased longitudinal bending stiffness (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019). Biomechanical studies conducted in high-calibre runners altogether indicate alterations in running kinetics and kinematics in VP4 compared to lightweight and common marathon footwear (Barnes & Kilding, 2019; Hoogkamer et al., 2018, 2019; Hunter et al., 2019), with common findings of lower step frequencies, longer step lengths, and longer contact times in VP4.

More specifically, the first study involving a VP4 prototype reported greater peak vertical ground reaction forces, lower step frequencies, longer step lengths, and longer contact times in VP4 compared to a Nike marathon racing shoe (Zoom Streak 6; Hoogkamer et al., 2018). This study also reported lower step frequencies and longer step lengths than the Adidas Adizero Adios BOOST 2(Hoogkamer et al., 2018). In a more detailed biomechanical report involving the same footwear, Hoogkamer et al. (2019) found lesser ankle dorsiflexion angles during stance, peak ankle moments, ankle work, peak metatarsophalangeal dorsiflexion, peak metatarsophalangeal dorsiflexion velocity, and negative metatarsophalangeal work running in VP4. When compared to lightweight track spikes, high-calibre runners running in VP4 have been shown to exhibit longer contact and flight times, lower stride frequencies, and longer strides (Barnes & Kilding, 2019). All of these biomechanical studies have involved high-calibre runners, and not recreational runners who represent the largest group of runners in the community (Honert et al., 2020).

CONTACT Kim Hébert-Losier kim.hebert-losier@waikato.ac.nz Division of Health, Engineering, Computing and Science, Te Huataki Waiora School of Health, University of Waikato, Tauranga, New Zealand

Runners with less experience tend to adapt differently to various running conditions from a biomechanical standpoint compared with high-calibre runners (Boyer et al., 2014; Hébert-Losier et al., 2015; Maas et al., 2018; Millet et al., 2010), with training status identified as a potential injury risk factor in different footwear conditions (Tam et al., 2017). Recently, we reported meaningful, albeit variable and individual, average improvements in treadmill-based running economy and time-trial measures in recreational runners wearing VP4(Hébert-Losier et al., 2020). Our aims were to conduct an exploratory analysis to compare the running kinematics of male recreational runners wearing the commercially available Nike Vaporfly 4% (VP4), the Saucony Endorphin Racer 2 lightweight racing flat (FLAT), and their own habitual running shoes (OWN). Given that biomechanical factors can affect running economy (Moore, 2016), a secondary aim was to explore potential relationships between kinematic and physiological differences based on shoe type.

2. Materials and methods

2.1. Participants

Sixteen male recreational runners (mean ± standard deviation age: 33 ± 12.0 y, height: 1.79 ± 0.06 m, mass: 77.0 ± 8.7 kg, body mass index: 23.9 ± 2.5 kg · m^{-2}, $\dot{V}O_{2peak}$: 55.2 ± 4.3 ml · kg^{-1} · min^{-1}, and recent 5-km time 21:21.3 ± 02:03.5) completed the experimental protocol. These participants were involved in a larger study seeking to compare the physiological and biomechanical differences between running in VP4, FLAT, and OWN, with the current paper addressing the biomechanical differences. Runners ran three times a week and 24 km per week (median values, interquartile ranges: 2-4 times and 14–39 km, respectively), and had been running for at least 2 years (median value, interquartile range: 5–26 years). Runners were recruited through personal contacts, running clubs, social media, and word-of-mouth. Inclusion criteria were male runners with a 5-km run time of ~20–25 minutes within the past 3 months and running regularly to reflect a "recreational" runner (Honert et al., 2020). Runners with current or recent (<3 months) injuries were excluded. All participants provided written informed consent and were informed of the potential injury risks (e.g., musculoskeletal injuries linked with running in novel footwear (Ridge et al., 2013) and delayed onset muscle soreness). The experiment was approved by our institution's Human Research Ethics Committee [HREC(Health)2018#81] and abided by the ethical standards of the Declaration of Helsinki.

2.2. Design and methodology

The effect of footwear on the running kinematics at three submaximal running speeds was assessed using a randomised crossover study design that required participants to attend four laboratory sessions (see Supplementary **Figure S1**). In the first session, baseline measures from participants (age, height, mass, body mass index, recent 5-km run times, and OWN shoe characteristics) and $\dot{V}O_{2peak}$ were collected, and familiarisation runs with VP4 and FLAT were performed. These two experimental footwear conditions were selected as both shoe types were available for consumer purchase at the time of the study (i.e., not prototypes) and were considered high-end racing shoes. An additional key consideration for the FLAT was low footwear mass. The Saucony Endorphin Racer 2 (~150 g) fitted these criteria. By design, we did not modify the shoe mass and instead sought to maintain the ecological validity of the acquired data. The motorised treadmill (Steelflex PT10 Fitness, Steelflex Fitness, Taipei, Taiwan) used throughout this study had an average surface stiffness of 365 kN · m^{-1} (Hébert-Losier et al., 2020)reflective of a "hard" treadmill surface (Hardin et al., 2004).

Given that knowledge of shoe brand can affect perceived shoe comfort (Hennig & Schulz, 2011) and potential running performance (Hoogkamer et al., 2016; Hunter et al., 2019), we spray-painted the VP4 and FLAT shoes black in an attempt to blind participants to footwear brand and model (**Figure S1**). In the second, third, and fourth sessions, the running kinematics at 60%, 70%, and 80% of the speed found to elicit $\dot{V}O_{2peak}$ ($v\dot{V}O_{2peak}$) were assessed in one of the footwear conditions in a randomised counterbalanced manner. Four to seven days (6.5 ± 0.9 days) separated the sessions, with a maximum of 14 days between the first and last kinematic session. Participants were tested at the same time of day and asked to replicate their nutrition, sleep, and training patterns prior to each session, which was confirmed using a self-reported log. All tests were performed in a temperature-controlled laboratory (temperature: 18–20°C, humidity: 55–60%). Examination of relative (percentage of $\upsilon\dot{V}O_{2peak}$) rather than absolute running speeds was chosen to individualise speeds and in consideration that running technique varies depending on the running economy of individuals (Tartaruga et al., 2012).

2.2.1. Visit 1

Baseline information; anthropometric characteristics; and the mass, make, and model of participants' OWN shoes were recorded in Visit 1. Participants self-selected their OWN shoes knowing they were being asked to perform a $\dot{V}O_{2peak}$ test and running trials at various speeds on a treadmill. We also assessed participants' OWN shoes using the minimalist index, a valid and reliable tool used to determine the level of minimalism of running shoes (Esculier et al., 2015). Briefly, the minimalist index considers five key characteristics to establish the degree of minimalism of shoes, where 100% represents the highest level of minimalism and 0% the lowest. Shoe-related characteristics are presented in Table 1.

Table 1. Shoe characteristics, comfort, and experience. Data are mean ± standard deviation values from 16 male runners.

Characteristics	OWN	FLAT	VP4
Mass (g)	321 ± 40	154 ± 7	213 ± 12
Stack height (mm)	26.6 ± 8.2	13.0 ± 0	31.0 ± 0
Heel-to-toe drop (mm)	9.5 ± 7.1	1.0 ± 0	7.0 ± 0
Minimalist index (%)†	35 ± 17	88 ± 0	48 ± 0
VAS comfort immediate (0–100)	79 ± 13	50 ± 29	67 ± 32
VAS experience (0–100)	88 ± 13	24 ± 30	26 ± 33
VAS comfort post running (0–100)	76 ± 16	55 ± 20	59 ± 23

Notes. OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%. VAS, visual analogue scale. Data from right shoes only (size: US 8.5–12). †Minimalist index range: 0% (lowest) to 100% (highest) degree of minimalism.

Participants then tried the two experimental footwear conditions to ensure proper fit, jogging around the laboratory. Immediate shoe comfort and experience in VP4, FLAT, and OWN were recorded using a 0–100 mm visual analogue scale (VAS) with corresponding anchor points of "not comfortable at all" to "most comfortable imaginable", and "no experience at all (beginner)" to "maximal experience (expert)". The VAS data are reported in Table 1.

Participants subsequently completed a 4-minute warm-up at 10 km · h^{-1} running with their own shoes on the treadmill prior to completing a $\dot{V}O_{2peak}$ ramp test using an incremental speed protocol and 1% incline to assess maximal aerobic power. The test started at 10 km · h^{-1} and increased 1 km · h^{-1} per minute until volitional exhaustion. The mean $v\dot{V}O_{2peak}$ was 18.4 ± 1.0 km · h^{-1}. After a 10-minute rest, participants ran 2 × 3 minutes at a self-selected speed on the treadmill once in VP4 and once in FLAT for shoe familiarisation, with 1-minute rest between footwear conditions.

2.2.2. Visits 2, 3 and 4

Lower-body kinematics in VP4, FLAT, and OWN were assessed in Visits 2, 3, and 4 using a calibrated 8-camera Oqus 700+ 3D motion capture system sampling at 300 Hz using the Qualisys Track Manager software version 2019.1 (build 4400, Qualisys AB, Gothenburg, Sweden). Comparable to the $\dot{V}O_{2peak}$ ramp test, the treadmill incline was set to a 1% grade to more accurately reflect the energetic cost of outdoor running (Jones & Doust, 1996). At the start of each session, 36 × 12.5-mm retro-reflective markers were affixed over anatomical landmarks and shoes based on the Calibrated Anatomical System Technique (Cappello et al., 1997) and established guidelines (Grood & Suntay, 1983). All 36 markers were used for the 1-second static calibration trial prior to experimentation, and 8 markers were removed for the running efforts (Figure 1). The same experienced assessor positioned markers on participants for each laboratory session. Most sagittal plane kinematic parameters extracted from treadmill running 3D motion capture demonstrate good-to-excellent between-week reliability (Bramah et al., 2021). Although metatarsophalangeal joint kinematics have been reported to differ between footwear conditions (Hoogkamer et al., 2019), markers were not placed to monitor 3D motion at the metatarsophalangeal joint as it was inappropriate to cut holes in participants' OWN shoes to place markers directly on their skin (Arnold & Bishop, 2013; Sinclair et al., 2014).

Participants ran a 2-minute self-selected speed warm-up in their allocated shoe condition and completed 3 × 3-minute bouts at 60% (11.1 ± 0.6 km · h^{-1}), 70% (12.9 ± 0.7 km · h^{-1}), and 80% (14.8 ± 0.8 km · h^{-1}) of $\upsilon\dot{V}O_{2peak}$ separated by a 1-minute rest. The 3D marker trajectories were collected for 30 seconds from the 2nd minute of each 3-minute bout, thereby allowing 4 minutes from the start of the running trial to the first 3D data collection period to enable stabilisation of footwear properties (Divert et al., 2005). Throughout the 3-minute constant-speed bouts, expired gases were continuously measured

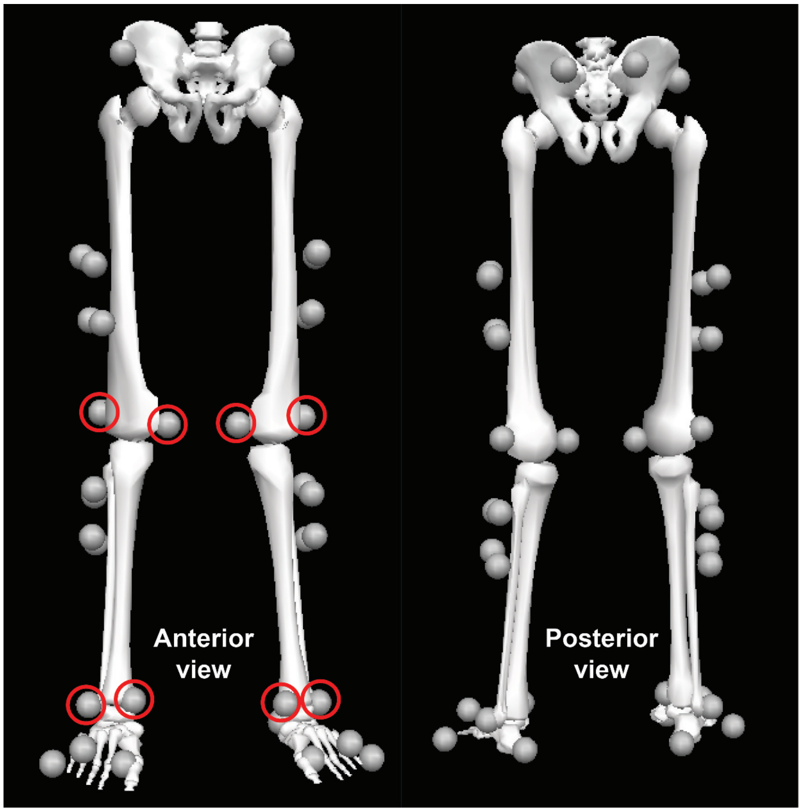

Figure 1. Marker placement for 3D motion capture of the runner. Anatomical reference markers on the runner were placed bilaterally on the: anterior and posterior superior iliac spines; medial and lateral femoral epicondyles; medial and lateral malleoli; and heel, first, second, and fifth metatarsal heads. Tracking markers on the runner were placed bilaterally on the lateral aspects of the thigh and shank using 4-marker rigid clusters. The red circles indicate markers that were removed for the running trials (shown for anterior view only).

using a calibrated metabolic cart (True One 2400; Parvo Medicks, Salt Lake City, UT, USA) and used to determine oxygen consumption ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), energy cost (power, $\text{W} \cdot \text{kg}^{-1}$) and energetic cost of transport (energy, $\text{J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$) as described in detail elsewhere (Hébert-Losier et al., 2020). Across physiological measures, lower values indicate better running economy. Following the last 3-minute bout at 80% of $\upsilon\dot{V}O_{2peak}$, participants rated their perceived shoe comfort on the comfort VAS (Table 1). At the end of all experimental sessions, participants were asked whether they knew what shoes they had been tested in. None of the 16 runners correctly identified the make or model of the two experimental footwear.

2.3. Data processing

The raw 3D marker trajectory data were exported to the .c3d format and processed using Visual3D Professional^{TM} software version 6.03.6 (C-Motion Inc., Germantown, Maryland, USA) and MATLAB R2017b version 9.3.0.713579 (The MathWorks, Inc., Natick, Massachusetts, USA). From the reference markers, a lower-body biomechanical model with six degrees of freedom at each joint and seven rigid segments was constructed. The local coordinates of the pelvis, thighs, shanks, and feet were derived from the calibration trial with a CODA pelvis used to define the hip-joint centres (Bell et al., 1989). The X-axis, Y-axis, and Z-axis of the virtual laboratory were aligned with the medial-lateral (right-left), anterior-posterior, and superior-inferior directions, respectively. Any gaps in the marker trajectory data up to 20 frames were interpolated using a third order polynomial fit algorithm. Marker data were then filtered using a fourth order low-pass Butterworth filter with a cut-off frequency of 20 Hz.

Several kinematic-based algorithms were tested for the automatic detection of footstrike and toe-off events based on procedures described in the literature (Fellin et al., 2010; Hébert-Losier et al., 2015; Maiwald et al., 2009; Patoz et al., 2019). The most robust algorithms for detecting events across participants and shoe conditions were selected through confirmation of event detected using sagittal plane videos. For event detection, a mid-toe landmark was generated as the mean position of the first, second, and fifth metatarsal markers. The footstrike algorithm identified the time indexes of maximum positive vertical acceleration of the mid-toe landmark and calcaneus marker. The footstrike event was searched for within a time window of 5 frames before and 30 frames after maximum anterior position of the mid-toe landmark in the respective strides to eliminate acceleration peaks not associated with ground contact. The toe-off event was defined as the first frame in each stride in which the vertical position of the mid-toe raised past a threshold of 0.025 m above the global minimum. These events were used to compute spatiotemporal gait parameters: step frequency ($\text{steps} \cdot \text{min}^{-1}$), step length (cm), flight time (ms), and contact time (ms).

In addition to spatiotemporal parameters, kinematic waveforms were generated using rigid-body analysis Euler angles obtained from the static calibration, and the right-hand rule sign convention. Body angles in the sagittal, coronal, and transverse planes were calculated using an X-Y-Z cardan sequence equivalent to the joint coordinate system proposed by Grood and Suntay (1983). Noteworthy, only the flexion-extension Cardan angles were considered for analysis due to possible errors linked with kinematic crosstalk (Kadaba et al., 1990). To create more clinically relevant ankle joint angles, virtual foot segments were constructed using the calcaneus marker as proximal joint centre with the y-axis directed through the projection of the 2nd metatarsal marker onto the plane created by the first and fifth metatarsal markers.

The kinematic parameters extracted for the analysis were based on previous studies reporting distinct kinematic features in VP4 (Barnes & Kilding, 2019; Hoogkamer et al., 2019) and included ranges of motion (ROM) and instantaneous joint angles (in degrees). More specifically, foot-ground angle at footstrike adjusted to the static calibration trial (Altman & Davis, 2012); ankle, knee, and hip ROM during stance; peak ankle dorsiflexion during stance; late stance (i.e., propulsive) peak plantarflexion velocity (degrees per second); hip ROM during swing; and vertical pelvis displacement (cm) were extracted from both the right and left sides. Runners were categorised as rearfoot strikers when the foot-ground angle was greater than 8° at ground contact, and non-rearfoot strike when ≤8°(Altman & Davis, 2012). Footstrike pattern was determined for each ground strike. Twenty strides (40 steps) from each 30-second kinematic data collection were extracted for statistical analysis.

2.4. Statistical analysis

Kinematic data were analysed using boxplots implemented in MATLAB (Hummersone, 2020), which show data distributions for each intensity and footwear condition within each spatiotemporal and kinematic parameter. This approach was chosen as appropriate for exploratory analyses (Chambers et al., 2018) and enables clear visualisation of data distributions, including median, interquartile range (IQR), participant means, and outliers. Boxplots also allow informal pairwise comparisons between footwear conditions. In each plot, the notch is centred on the median and extends to $\pm 1.58 * \text{IQR}/\sqrt{N}$, which is the 95% confidence interval of the median, where N represents the sample size and includes 20 strides (40 steps) from each one of the 16 participants. Median values can be judged to differ significantly if the notches of the corresponding boxplots do not overlap (Chambers et al., 2018; Cumming, 2009; Krzywinski & Altman, 2014). In the instances when notches between plots do not overlap, differences in median values (Δ_{median}) between footwear conditions are presented in the results.

To explore potential relationships between biomechanical and physiological changes linked to footwear, the mean for each participant, intensity, and shoe for each kinematic and running economy variable was extracted. The biomechanical and physiological differences for each shoe comparison were plotted, and Pearson correlation coefficients (r) with 95% confidence intervals computed. The existence of a *moderate* relationship, defined as $|r| \geq 0.30$(Cohen, 1992), was deemed to reflect a potentially meaningful relationship between biomechanical and physiological changes worthy of further exploration in future research.

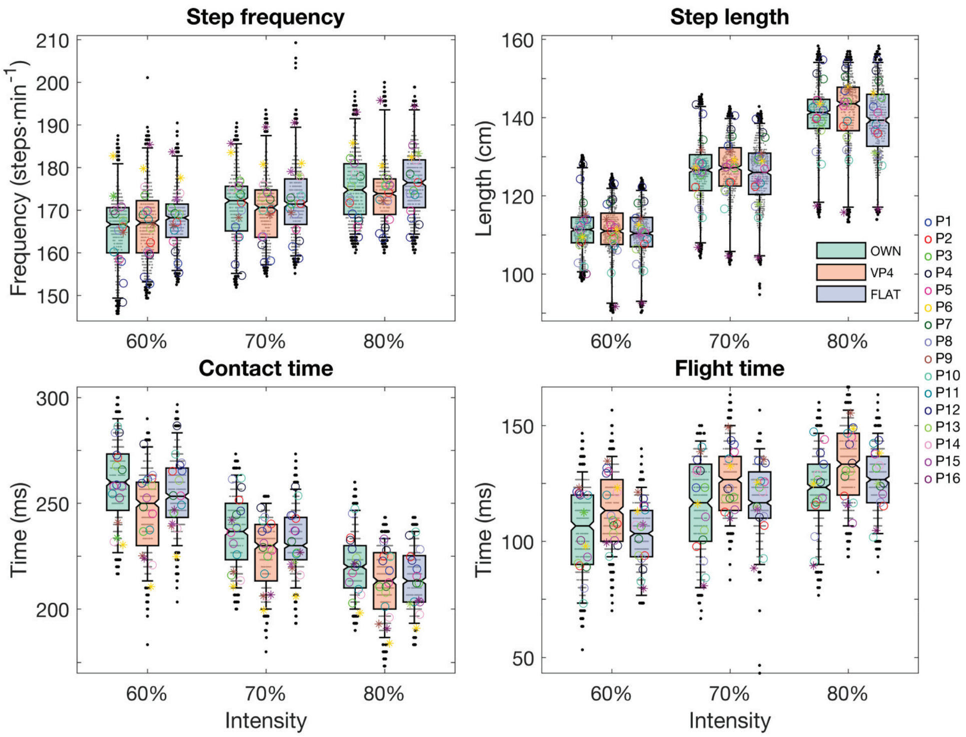

Figure 2. Boxplots of the spatiotemporal parameters extracted for each intensity (60%, 70%, and 80% of the speed that elicited VO_{2peak}) and footwear (OWN, VP4, and FLAT) condition. All data points are shown. Whiskers extend out above and below the median by 1.5 × IQR, where IQR is the interquartile range. Data beyond the whiskers are shown as outliers. Circles and stars represent the mean of the 20 strides (40 steps) from individuals with mean foot-ground angles >8° (rearfoot strike) and ≤8° (non-rearfoot strike) in that footwear-intensity condition, respectively. The notches can be used for informal pairwise comparisons of median levels between footwear conditions. Median values can be judged to differ significantly if the notches of the corresponding boxplots do not overlap. OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%.

3. Results

Boxplots of the spatiotemporal are shown in Figure 2, whereas those representing the kinematics parameters are shown in Figures 3 and 4. The median and IQR values for each footwear condition and intensity are provided as supplementary material (**Table S1**), as are the differences in median values between footwear conditions (**Table S2**).

VP4 involved longer flight times across intensities (Δ_{median} = 6.7 to 10.0 ms) and longer step lengths at 80% (Δ_{median} = 2.2 to 4.2 cm) than the two other footwear conditions, and longer contact times than OWN across intensities (Δ_{median} = 6.7 to 10.0 ms), as indicated in Figure 2 and reported in **Table S2**. At the greatest intensity, FLAT was associated with higher step frequencies (Δ_{median} = 1.7 to 2.6 steps $\cdot$ min^{-1}) and shorter step lengths (Δ_{median} = 2.0 to 4.2 cm) than the other two conditions, as well as longer flight times than OWN (Δ_{median} = 3.3 ms).

In terms of kinematics, differences between footwear conditions are visualised in Figures 3 and 4, and data reported in **Table S2**. FLAT exhibited smaller foot-ground angles (i.e., less rearfoot) than VP4 (Δ_{median} = 2.5° to 3.6°) and OWN (Δ_{median} = 2.6° to 3.2°), and greater peak dorsiflexion in stance (Δ_{median} = 2.1° to 2.6° and Δ_{median} = 1.2° to 1.8°) across intensities. Peak plantarflexion velocities in the late stance were lowest in VP4 (Δ_{median} = 58.8 to 108.5 deg $\cdot$ s^{-1}) and greatest in FLAT (Δ_{median} = 11.3 to 89.0 deg $\cdot$ s^{-1}) across intensities. Ankle ROM in stance was lowest in VP4 (Δ_{median} = 2.4° to 3.9°) and greatest in FLAT (Δ_{median} = 1.0° to 3.9°); knee ROM was comparable between shoes; hip ROM in both stance (Δ_{median} = 2.5° to 4.2°) and swing (Δ_{median} = 1.4° to 2.3°) were lowest in VP4 across intensities (except in swing at 80% vs OWN). The VP4 shoes were associated with greater vertical pelvis displacement than FLAT across intensities, as well as when compared to OWN but only at 70% (Δ_{median} = 0.3 to 0.4 cm).

Physiological data for the individual shoe conditions are reported in **Table S3** and median differences in **Table S4**. Combining the three physiological variables, median values were on average 5.2% greater in OWN than VP4, 2.6% greater in OWN than FLAT, and 2.5% greater in FLAT than VP4 across intensities, where greater values indicate less economical running patterns.

With regard to potential relationships between biomechanical and physiological changes linked to footwear, lower step frequencies and longer step lengths; increases in knee ROM, hip ROM, and peak dorsiflexion angles in stance; and greater pelvis displacements were moderately correlated to increases in oxygen consumption, energy cost, and energetic cost of transport in OWN compared to VP4 ($|r| \geq 0.30$, **Figure S2**). The only exception was for differences in peak dorsiflexion angles in stance and oxygen consumption ($r = 0.23$, **Figure S2**). Lower step frequencies and longer step lengths were also moderately correlated to increases in oxygen consumption and energetic cost of transport in OWN compared to FLAT. There were no other meaningful correlations (i.e., $|r| \geq 0.30$) between changes in biomechanical and physiological variables across shoe comparisons, with none of the biomechanical differences between VP4 and FLAT explaining changes in running economy

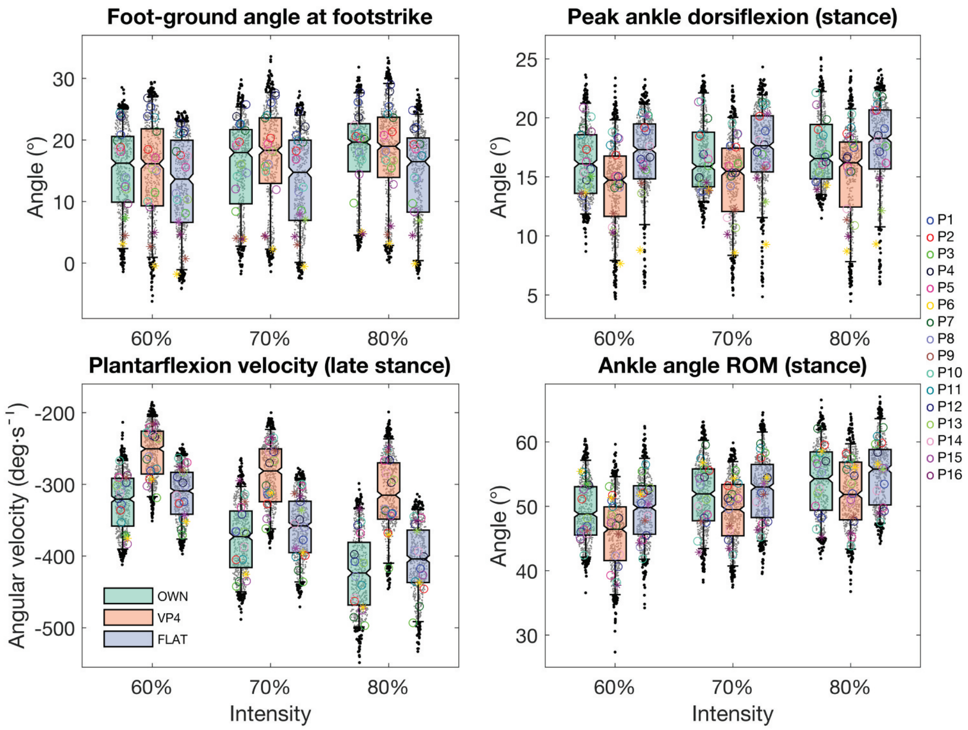

Figure 3. Boxplots of the kinematic parameters extracted at the foot and ankle for each intensity (60%, 70%, and 80% of the speed that elicited VO_{2peak}) and footwear (OWN, VP4, and FLAT) condition. All data points are shown. Whiskers extend out above and below the median by 1.5 × IQR, where IQR is the interquartile range. Data beyond the whiskers are shown as outliers. Circles and stars represent the mean of the 20 strides (40 steps) from individuals with mean foot-ground angles >8° (rearfoot strike) and ≤8° (non-rearfoot strike) in that footwear-intensity condition, respectively. The notches can be used for informal pairwise comparisons of median levels between footwear conditions. Median values can be judged to differ significantly if the notches of the corresponding boxplots do not overlap. OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%. ROM, range of motion.

variables. The correlation and 95% confidence interval values for each footwear comparison are given in supplementary material (**Table S3**).

4. Discussion

The current study adds to the body of knowledge on VP4 and FLAT footwear from an independent laboratory, and is the first to observe that VP4 alters kinematics in recreational runners compared to their habitual footwear and lightweight minimal shoes. Given the risks associated with changing biomechanical patterns in uninjured runners (Anderson et al., 2019) and transitioning to novel footwear too quickly (Ridge et al., 2013), caution is advised to recreational runners seeking to improve performance through acute footwear interventions.

Our biomechanical findings align with the first published laboratory-based studies in competitive runners wearing VP4 (Hoogkamer et al., 2018; Hoogkamer et al., 2019), whereby running in VP4 generally involved longer step lengths, longer flight times, lower step frequencies, and smaller peak dorsiflexion angles during stance, especially when compared to FLAT. A subsequent study involving competitive runners reported longer contact times in VP4 compared to lightweight track spikes (Barnes & Kilding, 2019). This comparison with thinner soled shoes was not confirmed when analysing VP4 and FLAT. This difference in kinematic outcomes between studies is likely due to several factors. Our minimal footwear was slightly heavier (~36 g) and had no spikes compared to the Nike Zoom Matumbo 3 track spikes (Barnes & Kilding, 2019). Our runners ran at slower and relative (percentage of υV̇) running speeds rather than absolute ones. Differences in treadmill compliance levels (Gidley et al., 2020) and use of 3D vs. 2D motion capture methods to derive parameters (Michelini et al., 2020; Mousavi et al., 2020) can also contribute to differences in findings. In addition, our runners expressed relatively low comfort and familiarity to running in the racing flats (Table 1) and may have been less familiar with such footwear compared to competitive runners. Nonetheless, our participants' lower comfort in FLAT is unlikely to underpin the biomechanical differences observed, as suggested by previous research findings indicating no significant changes in running biomechanical variables between the most and least comfortable shoes (Chan et al., 2020; Lindorfer et al., 2020).

Despite the majority of our participants remaining rearfoot strikers in FLAT (based on foot-ground angles being >8°; Altman & Davis, 2012), foot-ground angles were lower in FLAT versus OWN and VP4. This finding was anticipated given that running in more minimal compared to more conventional and/or cushioned shoes typically reduces foot-ground angles (Lussiana et al., 2013; Squadrone et al., 2015) and increases the relative plantar pressure in the forefoot region (Fuller et al., 2017; Lussiana et al., 2016). Ankle ROM in stance was also larger in FLAT, agreeing with findings from Hannigan and Pollard (2020) of greater ankle ROM in minimal versus traditional and maximal shoes. Minimal shoe running alters the loading profile at the foot and ankle and increases calf and Achilles tendon loads, suggesting that transitioning to minimal

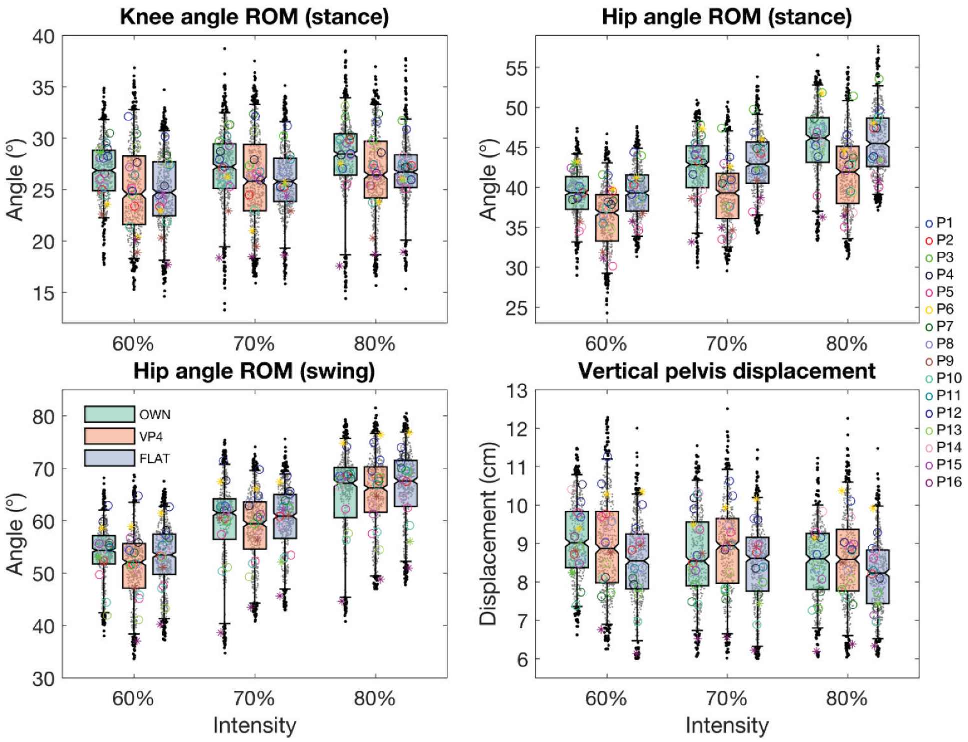

Figure 4. Boxplots of the kinematic parameters extracted at the knee, hip and pelvis for each intensity (60%, 70%, and 80% of the speed that elicited VO_{2peak}) and footwear (OWN, VP4, and FLAT) condition. All data points are shown. Whiskers extend out above and below the median by 1.5 × IQR, where IQR is the interquartile range. Data beyond the whiskers are shown as outliers. Circles and stars represent the mean of the 20 strides (40 steps) from individuals with mean foot-ground angles >8° (rearfoot strike) and ≤8° (non-rearfoot strike) in that footwear-intensity condition, respectively. The notches can be used for informal pairwise comparisons of median levels between footwear conditions. Median values can be judged to differ significantly if the notches of the corresponding boxplots do not overlap. OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%. ROM, range of motion.

shoes should be gradual, progressive, and potentially incorporate calf and foot strengthening beforehand (Davis, 2014; Warne & Gruber, 2017) to reduce injury risk during transitioning.

In contrast, peak dorsiflexion angle during stance, ankle ROM during stance, and plantarflexion velocity in late stance were all lower in VP4, notably when compared to FLAT. This lesser involvement of the ankle joint in VP4 agrees with findings of reduced positive and negative ankle work reported by Hoogkamer et al. (2019), suggestive of lesser energy storage in the triceps surae muscle-tendon unit. Although this reduced involvement of the triceps surae muscle-tendon unit likely underpins some of the associated metabolic energy savings reported in the literature (Barnes & Kilding, 2019; Hébert-Losier et al., 2020; Hoogkamer et al., 2018; Hunter et al., 2019), the longer-term relative unloading of these structures could lead to reductions in the mechanical properties of the intrinsic and extrinsic muscles and tendons of the foot (i.e., cross-sectional area, stiffness, and strength), as indicated in studies comparing the longer-term adaptations to running in different footwear (Chen et al., 2016; Fuller et al., 2018; Histen et al., 2017).

Vertical pelvis displacement (i.e., vertical bouncing) was larger in VP4 than FLAT across running intensities, in agreement with the longer flight times we observed and prior studies involving VP4 footwear (Hunter et al., 2019). Differences in vertical motion between OWN and VP4 were, however, inconsistent across intensities. A novel finding was lesser ROM at the hip in VP4 compared to the other footwear conditions, notably in stance. Although the boxplots did not overlap, the ~3° difference might have limited practical relevance given the relatively lower repeatability of sagittal plane running kinematics at the hip compared to the knee and ankle (Bramah et al., 2021; Noehren et al., 2010). In recreational runners, small changes in hip motion at faster running speeds may have limited practical value, with increases in hip power likely of greater importance (Orendurff et al., 2018).

Our exploratory scatterplot analysis highlighted kinematic variables at least moderately related to running economy, with higher step frequencies and shoter step lengths in the two experimental footwear conditions associated with improved running economy versus OWN. Self-selected step frequencies in novice runners are on average 8% lower than their most economical ones (De Ruiter et al., 2014). Even in experienced runners who self-select step frequencies closer to their most economical one (i.e., 3% difference), a 10-day training programme in well-trained female runners designed to increase step frequency can substantially benefit running economy and lower oxygen cost on average by 7% (Quinn et al., 2021). Our analysis indicates that those runners who increased their step frequencies and shortened their step lengths in VP4 and FLAT compared to OWN potentially benefited more from a physiological perspective, which could be a factor underpinning the variability in running economy responses with changes in footwear (Hébert-Losier et al., 2020). It is likely that the increased step frequency and improved running economy were driven, at least in part, by the lighter shoe mass of the two experimental footwear in comparison to OWN (see, Table 1). Compared to OWN, the exploratory scatterplot analysis indicated that running in VP4 was associated with greater improvements in running economy when running with lesser knee ROM, hip ROM, and peak dorsiflexion angles in stance, and lesser vertical pelvis motion. It could be that certain biomechanical changes that were moderately related to changes in the running economy were themselves interrelated, making it difficult to ascertain which biomechanical factor is more strongly mediating the physiological benefits. Our scatterplots nonetheless support the notion that VP4 footwear affects runners differently and that their biomechanical responses can impact their physiological ones.

There is scientific debate regarding the relative contribution of VP4 features on the energetic cost and performance of runners, with Nigg et al. (2020) proposing that the curved stiff sole and its resulting effects contribute the most to the improved running performance reported in VP4. Our research did not set out to examine the relative contributions of the various components of the VP4 and their effect on running gait, but rather sought to describe biomechanical differences in commercially available shoes to inform recreational runners and footwear prescription. Given that sex influences running biomechanics (Ferber et al., 2003) and footwear responses (Kim et al., 2021), findings from our study are not generalisable to female runners. Only acute effects were evaluated here, which were relatively small. Our results cannot be used to establish the minimum time or training volume required to adapt to novel footwear or to determine whether biomechanical differences remain with habituation to VP4 or FLAT. The use of individuals' OWN footwear has the potential to confound results given their variable characteristics (Table 1). Nonetheless, we maintain that examining changes due to novel unaltered footwear in relation to individuals' habitual running shoes enhances the ecological validity of findings as the changes further reflect real-life situations and off-the-shelf purchases.

5. Conclusion

Our exploratory analysis provides indications that the running kinematics of male recreational runners differ with acute exposure to VP4 and lightweight minimal racing flats when compared with their own shoes. A subset of these biomechanical changes was moderately related to changes in running economy, with both higher step frequencies and shorter step lengths in the two experimental footwear (i.e., VP4 and FLAT) associated with improved economy compared to OWN. Given the risks associated with changing biomechanical patterns in uninjured recreational runners and transitioning to novel footwear too quickly, our findings suggest that caution is advised when acutely changing footwear to improve performance. An accommodation period to adapt to novel footwear is advised, although the minimum time or training volume required to adapt to novel footwear remains unknown and is likely individual specific.

Acknowledgments

This work was internally funded by Te Huataki Waiora School of Health, University of Waikato, and The Running Clinic, Canada, and not endorsed by any footwear company.

Authors' contribution

KHL contributed to acquiring internal funding for this project, pilot testing, data extraction, statistical analysis with support from PFL, first draft of the manuscript, and supervising the project; SJF and IH contributed to the pilot testing, data extraction, and first draft of the manuscript; CMB contributed to the pilot testing. All authors were involved in the study design and ethical approval process, contributed to data interpretation and final draft of the manuscript, have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported that there is no funding associated with the work featured in this article.

ORCID

Kim Hébert-Losier http://orcid.org/0000-0003-1087-4986
Peter F. Lamb http://orcid.org/0000-0002-5928-8294
Matthew W. Driller http://orcid.org/0000-0002-9990-8830
Ivana Hanzlíková http://orcid.org/0000-0002-2259-9312
Blaise Dubois http://orcid.org/0000-0003-1089-9059
Jean-Francois Esculier http://orcid.org/0000-0003-0372-4525
Christopher Martyn Beaven http://orcid.org/0000-0003-2900-7460

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