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

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Abstract

We conducted an exploratory analysis to compare running kinematics of sixteen male recreational runners wearing Nike Vaporfly 4% (VP4) shoes, Saucony Endorphin lightweight racing flats (FLAT), and their habitual (OWN) footwear. We also explored potential relationships between kinematic and physiological changes. Runners (age: 33±12 y, $\dot{V}O_{2peak}$: 55.2±4.3 $ml \cdot kg^{-1} \cdot min^{-1}$) attended 3 sessions after completing an $\dot{V}O_{2peak}$ test in which sagittal plane kinematics at submaximal running speeds (60, 70, and 80% $\upsilon\dot{V}O_{2peak}$) were collected using 3D motion analysis alongside economy measures. Kinematics were compared using notched boxplots and between-shoe kinematic differences were plotted against changes in economy measures. Across intensities, VP4 involved longer flight times (6.7 to 10.0 ms) and lower stance hip ROM (~3°), and greater vertical pelvis displacement than FLAT (~0.4 cm). Peak dorsiflexion angles (~2°), ankle range (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 *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 at the ankle and in the spatiotemporal variables and foot-ground angles.

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[1-3], with ~0.7 to 1.1% lower energetic costs of running seen in footwear for every 100 g lighter mass[1,3]. Minimal footwear became an active area of research and interest to the running community[4] due to their lightweight characteristics and resemblance to barefoot running[5]. Compared to more traditional running shoes, running in minimal footwear generally promotes a more forefoot strike pattern, smaller footstrike angle, greater knee flexion at ground contact, and smaller knee flexion angles during stance[6].

More recently, improvements in world record running times are attributed to technological rather than physiological factors[7] as evidenced with 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[8-10]. Biomechanical studies conducted in high-calibre runners altogether indicate alterations in running kinetics and kinematics in VP4 compared to lightweight and common marathon footwear[8-11], 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)[9]. This study also reported lower step frequencies and longer step lengths than the Adidas Adizero Adios BOOST 2[9]. In a more detailed biomechanical report involving the same footwear, Hoogkamer et al.[11] 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[11]. 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[8]. All of these biomechanical studies have involved high-calibre runners, and not recreational runners who represent the largest group of runners in the community[12].

Runners with less experience tend to adapt differently to various running conditions from a biomechanical standpoint compared with high-calibre runners[13-16], with training status identified as a potential injury risk factor in different footwear conditions[17]. Recently, we reported meaningful, albeit variable and individual, average improvements in treadmill-based running economy and time-trial measures in recreational runners wearing VP4[18]. 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[19], 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 to 4 times and 14 to 39 km, respectively), and had been running for at least 2 years (median value interquartile range: 5 to 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[12]. 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[20] and delayed onset muscle soreness). The experiment was approved by our institution's Human Research Ethics Committee [HREC(Health)2018#81] and abided to the ethical standards of the Declaration of Helsinki.

2.2. Design and methodology

The effect of footwear on 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**). At 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 shoe mass and instead sought to maintain 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}[18] reflective of a "hard" treadmill surface[21].

Given that knowledge of shoe brand can affect perceived shoe comfort[22] and potentially performance[3,10], we spray-painted the VP4 and FLAT shoes black in an attempt to blind participants to footwear brand and model details (**Figure S1**). In the second, third, and fourth sessions, running kinematics at 60, 70, and 80% of the speed found to elicit $\dot{V}O_{2peak}$ ($\upsilon\dot{V}O_{2peak}$) 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%). The 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[23].

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[24]. 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*****

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 to 10 cm 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 $km \cdot h^{-1}$ 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 $km \cdot h^{-1}$ and increased 1 $km \cdot h^{-1}$ per minute until volitional exhaustion. The mean $\upsilon\dot{V}O_{2peak}$ was 18.4 ± 1.0 $km \cdot h^{-1}$. After a 10-minute rest, participants ran 2 x 3 minutes at a self-selected speed on the treadmill once in VP4 and once in FLAT for shoe familiarisation, with 1 minute of 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 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[25]. At the start of each session, 36 x 12.5-mm retro-reflective markers were affixed over anatomical landmarks and shoes based on the Calibrated Anatomical System Technique[26] and established guidelines[27]. 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[28]. Although metatarsophalangeal joint kinematics have been reported to differ between footwear conditions[11], 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[29,30].

*****FIGURE 1*****

Participants ran a 2-minute self-selected speed warm-up in their allocated shoe condition and completed 3 x 3-minute bouts at 60% [11.1 (0.6) $km\cdot h^{-1}$], 70% [12.9 (0.7) $km\cdot h^{-1}$], and 80% [14.8 (0.8) $km\cdot hr^{-1}$] 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[31]. Throughout the 3-minute constant-speed bouts, expired gases were continuously measured using a calibrated metabolic cart (True One 2400; Parvo Medics, Salt Lake City, UT, USA) and used to determine oxygen consumption ($mL\cdot kg^{-1}\cdot min^{-1}$), energy cost (power, $W\cdot kg^{-1}$), and energetic cost of transport (energy, $J\cdot kg^{-1}\cdot m^{-1}$) as described in detail elsewhere[18]. 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™ 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 was used to define the hip-joint centres[32]. 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[15,33-35]. 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 1st, 2nd, and 5th 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 in the respective stride to eliminate acceleration peaks not associated with ground contact. The toe-off event was defined as the first frame in each stride that 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 (steps·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[27]. Noteworthy, only the flexion-extension cardan angles were considered for analysis due to possible errors linked with kinematic crosstalk[36]. 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 1st and 5th metatarsal markers.

The kinematic parameters extracted for analysis were based on the previous studies reporting distinct kinematic features in VP4[8-11], 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[37]; 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 categorized as rearfoot strikers when the foot-ground angle was greater than 8° at ground contact, and non-rearfoot strike when ≤ 8°[37]. 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[38], 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[39] and enables clear visualisation of data distributions, including median, interquartile range, 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 $\pm 1.58 * \mathrm{IQR}/\sqrt{N}$, 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[39-41]. 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 $|\ r\ | \geq 0.30$[42], was deemed to reflect a potentially meaningful relationship between biomechanical and physiological changes worthy of further exploration in future research.

3. Results

Boxplots of the spatiotemporal are shown in **Figure 2**, whereas those representing the kinematics parameters are shown in **Figure 3** and **Figure 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·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).

*****FIGURE 2*****

In terms of kinematics, differences between footwear conditions are visualised in **Figure 3** and **Figure 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 late stance were slowest in VP4 (Δ_{median} = 58.8 to 108.5 deg·s^{-1}) and greatest in FLAT (Δ_{median} = 11.3 to 89.0 deg·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).

FIGURE 3

FIGURE 4

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 regards 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 variables. The correlation and 95% confidence interval values for each footwear comparison are 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[43] and transitioning to novel footwear too quickly[20], 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[9,11], whereby running in VP4 generally involved longer step lengths, longer flights 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[8]. This comparison with thinner soled shoes was not confirmed when analysing VP4 and FLAT. This difference in kinematic outcomes 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[8]. Our runners ran at slower and relative (percentage of $\upsilon\dot{V}O_{2peak}$) running speeds rather than absolute ones. Differences in treadmill compliance levels[44] and use of 3D vs 2D motion capture methods to derive parameters[45,46] 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 to 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 biomechanics variables between most and least comfortable shoes[47,48].

Despite the majority of our participants remaining rearfoot strikers in FLAT (based on foot-ground angles being > 8°)[37], 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[49,50] and increases the relative plantar pressure in the forefoot region[51,52]. Ankle ROM in stance was also larger in FLAT, agreeing with findings from Hannigan and Pollard[53] 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 shoes should be gradual, progressive, and potentially incorporate calf and foot strengthening beforehand[54,55].

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.[11], 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[8-10,18], 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[56-58].

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[10]. 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[28,59]. 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[60].

Our exploratory scatterplot analysis highlighted kinematic variables at least moderately related to running economy, with higher step frequencies and longer step lengths in the two experimental footwear associated with improved running economy versus OWN. Self-selected step frequencies in novice runners are on average 8% lower than their most economical one[61]. Even in experienced runners who self-select step frequencies closer to their most economical one (i.e., 3% difference), a 10-day training program in well-trained female runners designed to increase step frequency can substantially benefit running economy and lower oxygen cost on average by 7%[62]. 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[18]. 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 when 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 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.[63] 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[64] and footwear responses[65], 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-shelf purchases.

5. Conclusion

Our exploratory analysis provides indications that running kinematics of male recreational runners differ with acute exposure to VP4 and lightweight minimal shoes 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 longer 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.

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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.

Competing interest

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

References

1. Franz JR, Wierzbinski CM, Kram R. Metabolic cost of running barefoot versus shod: Is lighter better? *Med Sci Sports Exerc* 2012;**44**(8):1519-1525.

2. Fuller JT, Bellenger CR, Thewlis D, Tsiros MD, Buckley JD. The effect of footwear on running performance and running economy in distance runners. *Sports Med* 2015;**45**(3):411-422.

3. Hoogkamer W, Kipp S, Spiering BA, Kram R. Altered running economy directly translates to altered distance-running performance. *Med Sci Sports Exerc* 2016;**48**(11):2175-2180.

4. Rothschild CE. Primitive running: A survey analysis of runners' interest, participation, and implementation. *J Strength Cond Res* 2012;**26**(8):2021-2026.

5. Lieberman DE, Venkadesan M, Werbel WA, et al. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature* 2010;**463**(7280):531-535.

6. Perkins KP, Hanney WJ, Rothschild CE. The risks and benefits of running barefoot or in minimalist Shoes: A systematic review. *Sports Health* 2014;**6**(6):475-480.

7. Muniz-Pardos B, Sutehall S, Angeloudis K, Guppy FM, Bosch A, Pitsiladis Y. Recent improvements in marathon run times are likely technological, not physiological. *Sports Med* 2021;**51**(3):371-378.

8. Barnes KR, Kilding AE. A randomized crossover study investigating the running economy of highly-trained male and female distance runners in marathon racing shoes versus track spikes. *Sports Med* 2019;**49**(2):331-342.

9. Hoogkamer W, Kipp S, Frank JH, Farina EM, Luo G, Kram R. A comparison of the energetic cost of running in marathon racing shoes. *Sports Med* 2018;**48**(4):1009-1019.

10. Hunter I, McLeod A, Valentine D, Low T, Ward J, Hager R. Running economy, mechanics, and marathon racing shoes. *J Sports Sci* 2019;**37**(20):2367-2373.

11. Hoogkamer W, Kipp S, Kram R. The biomechanics of competitive male runners in three marathon racing shoes: A randomized crossover study. *Sports Med* 2019;**49**(1):133-143.

12. Honert EC, Mohr M, Lam W-K, Nigg S. Shoe feature recommendations for different running levels: A Delphi study. *PLoS One* 2020;**15**(7):e0236047.

13. Boyer KA, Freedman Silvernail J, Hamill J. The role of running mileage on coordination patterns in running. *J Appl Biomech* 2014;**30**(5):649-654.

14. Maas E, De Bie J, Vanfleteren R, Hoogkamer W, Vanwanseele B. Novice runners show greater changes in kinematics with fatigue compared with competitive runners. *Sports Biomech* 2018;**17**(3):350-360.

15. Hébert-Losier K, Mourot L, Holmberg HC. Elite and amateur orienteers' running biomechanics on three surfaces at three speeds. *Med Sci Sports Exerc* 2015;**47**(2):381-389.

16. Millet GY, Divert C, Banizette M, Morin J-B. Changes in running pattern due to fatigue and cognitive load in orienteering. *J Sports Sci* 2010;**28**(2):153-160.

17. Tam N, Coetzee DR, Ahmed S, Lamberts RP, Albertus-Kajee Y, Tucker R. Acute fatigue negatively affects risk factors for injury in trained but not well-trained habitually shod runners when running barefoot. *Eur J Sport Sci* 2017;**17**(9):1220-1229.

18. Hébert-Losier K, Finlayson SJ, Driller MW, Dubois B, Esculier J-F, Beaven CM. Metabolic and performance responses of male runners wearing 3 types of footwear: Nike Vaporfly 4%, Saucony Endorphin racing flats, and their own shoes. *J Sport Health Sci* 2020; doi: 10.1016/j.jshs.2020.11.012.

19. Moore IS. Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sports Med* 2016;**46**(6):793-807.

20. Ridge ST, Johnson AW, Mitchell UH, et al. Foot bone marrow edema after 10-week transition to minimalist running shoes. *Med Sci Sports Exerc* 2013;**45**(7):1363-1368.

21. Hardin EC, van den Bogert AJ, Hamill J. Kinematic adaptations during running: effects of footwear, surface, and duration. *Med Sci Sports Exerc* 2004;**36**(5):838-844.

22. Hennig E, Schulz J. Subjective evaluation of biomechanical shoe properties during blinded and non-blinded running. *Footwear Sci* 2011;**3**:S75-S76.

23. Tartaruga MP, Brisswalter J, Peyré-Tartaruga LA, et al. The relationship between running economy and biomechanical variables in distance runners. *Res Q Exerc Sport* 2012;**83**(3):367-375.

24. Esculier JF, Dubois B, Dionne CE, Leblond J, Roy JS. A consensus definition and rating scale for minimalist shoes. *J Foot Ankle Surg* 2015;**8**(42):1-9.

25. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J Sports Sci* 1996;**14**(4):321-327.

26. Cappello A, Cappozzo A, La Palombara PF, Lucchetti L, Leardini A. Multiple anatomical landmark calibration for optimal bone pose estimation. *Hum Mov Sci* 1997;**16**(2-3):259-274.

27. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: Application to the knee. *J Biomech Eng* 1983;**105**(2):136-144.

28. Bramah C, Preece SJ, Gill N, Herrington L. The between-day repeatability, standard error of measurement and minimal detectable change for discrete kinematic parameters during treadmill running. *Gait Posture* 2021;**85**:211-216.

29. Arnold JB, Bishop C. Quantifying foot kinematics inside athletic footwear: A review. *Footwear Sci* 2013;**5**(1):55-62.

30. Sinclair J, Taylor PJ, Hebron J, Chockalingam N. Differences in multi-segment foot kinematics measured using skin and shoe mounted markers. *FAOJ* 2014;**7**(2):1-7.

31. Divert C, Baur H, Mornieux G, Mayer F, Belli A. Stiffness adaptations in shod running. *J Appl Biomech* 2005;**21**(4):311-321.

32. Bell AL, Brand RA, Pedersen DR. Prediction of hip joint centre location from external landmarks. *Hum Mov Sci* 1989;**8**(1):3-16.

33. Fellin RE, Rose WC, Royer TD, Davis IS. Comparison of methods for kinematic identification of footstrike and toe-off during overground and treadmill running. *J Sci Med Sport* 2010;**13**(6):646-650.

34. Maiwald C, Sterzing T, Mayer TA, Milani TL. Detecting foot-to-ground contact from kinematic data in running. *Footwear Sci* 2009;**1**(2):111-118.

35. Patoz A, Lussiana T, Gindre C, Hébert-Losier K. Recognition of foot strike pattern in Asian recreational runners. *Sports* 2019;**7**(6):E147.

36. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *J Orthop Res* 1990;**8**(3):383-392.

37. Altman AR, Davis IS. A kinematic method for footstrike pattern detection in barefoot and shod runners. *Gait Posture* 2012;**35**(2):298-300.

38. Hummersone C. Alternative box plot, v2.8. 2020; https://www.github.com/IoSR-Surrey/MatlabToolbox. Accessed June 15, 2020.

39. Chambers JM, Cleveland WS, Kleiner B, Tukey PA. Graphical Methods for Data Analysis. Boca Raton, Florida: CRC Press; 2018.

40. Krzywinski M, Altman N. Visualizing samples with box plots. *Nat Methods* 2014;**11**(2):119-120.

41. Cumming G. Inference by eye: Reading the overlap of independent confidence intervals. *Stat Med* 2009;**28**(2):205-220.

42. Cohen J. A power primer. *Psychol Bull* 1992;**112**(1):155-159.

43. Anderson LM, Bonanno DR, Hart HF, Barton CJ. What are the benefits and risks associated with changing foot strike pattern during running? A systematic review and meta-analysis of injury, running economy, and biomechanics. *Sports Med* 2019;**50**(5):885-917.

44. Gidley AD, Lankford DE, Bailey JP. The construction of common treadmills significantly affects biomechanical and metabolic variables. *J Sports Sci* 2020;**38**(19):2236-2241.

45. Michelini A, Eshraghi A, Andrysek J. Two-dimensional video gait analysis: A systematic review of reliability, validity, and best practice considerations. *Prosthet Orthot Int* 2020;**44**(4):245-262.

46. Mousavi SH, Hijmans JM, Moeini F, et al. Validity and reliability of a smartphone motion analysis app for lower limb kinematics during treadmill running. *Phys Ther Sport* 2020;**43**:27-35.

47. Lindorfer J, Kröll J, Schwameder H. Does enhanced footwear comfort affect oxygen consumption and running biomechanics? *Eur J Sport Sci* 2020;**20**(4):468-476.

48. Chan ZYS, Au IPH, Zhang JH, et al. Effects of deceptive footwear condition on subjective comfort and running biomechanics. *Transl Sports Med* 2020;**3**(3):256-262.

49. Squadrone R, Rodano R, Hamill J, Preatoni E. Acute effect of different minimalist shoes on foot strike pattern and kinematics in rearfoot strikers during running. *J Sports Sci* 2015;**33**(11):1196-1204.

50. Lussiana T, Fabre N, Hebert-Losier K, Mourot L. Effect of slope and footwear on running economy and kinematics. *Scand J Med Sci Sports* 2013;**23**(4):246-253.

51. Fuller JT, Thewlis D, Tsiros MD, Brown NAT, Buckley JD. Six-week transition to minimalist shoes improves running economy and time-trial performance. *J Sci Med Sport* 2017;**20**(12):1117-1122.

52. Lussiana T, Hébert-Losier K, Millet GP, Mourot L. Biomechanical changes during a 50-minute run in diferent footwear and on various slopes. *J Appl Biomech* 2016;**32**(1):40-49.

53. Hannigan JJ, Pollard CD. Differences in running biomechanics between a maximal, traditional, and minimal running shoe. *J Sci Med Sport* 2020;**23**(1):15-19.

54. Davis IS. The re-emergence of the minimal running shoe. *J Orthop Sports Phys Ther* 2014;**44**(10):775-784.

55. Warne JP, Gruber AH. Transitioning to minimal footwear: A systematic review of methods and future clinical recommendations. *Sports Med Open* 2017;**3**(1):33.

56. Histen K, Arntsen J, L'Hereux L, et al. Achilles tendon properties of minimalist and traditionally shod runners. *J Sport Rehabil* 2017;**26**(2):159-164.

57. Chen TL, Sze LK, Davis IS, Cheung RT. Effects of training in minimalist shoes on the intrinsic and extrinsic foot muscle volume. *Clin Biomech (Bristol, Avon)* 2016;**36**:8-13.

58. Fuller JT, Thewlis D, Tsiros MD, Brown NAT, Hamill J, Buckley JD. Longer-term effects of minimalist shoes on running performance, strength and bone density: A 20-week follow-up study. *Eur J Sport Sci* 2018;**19**(3):402-412.

59. Noehren B, Manal K, Davis I. Improving between-day kinematic reliability using a marker placement device. *J Orthop Res* 2010;**28**(11):1405-1410.

60. Orendurff MS, Kobayashi T, Tulchin-Francis K, et al. A little bit faster: Lower extremity joint kinematics and kinetics as recreational runners achieve faster speeds. *J Biomech* 2018;**71**:167-175.

61. de Ruiter CJ, Verdijk PW, Werker W, Zuidema MJ, de Haan A. Stride frequency in relation to oxygen consumption in experienced and novice runners. *Eur J Sport Sci* 2014;**14**(3):251-258.

62. Quinn TJ, Dempsey SL, LaRoche DP, Mackenzie AM, Cook SB. Step frequency training improves running economy in well-trained female runners. *J Strength Cond Res* 2021;**35**(9):2511-2517.

63. Nigg BM, Cigoja S, Nigg SR. Effects of running shoe construction on performance in long distance running. *Footwear Sci* 2020;**12**(3):133-138.

64. Ferber R, Davis IM, Williams Iii DS. Gender differences in lower extremity mechanics during running. *Clin Biomech (Bristol, Avon)* 2003;**18**(4):350-357.

65. Kim HK, Mirjalili SA, Zhang Y, Xiang L, Gu Y, Fernandez J. Effect of gender and running experience on lower limb biomechanics following 5 km barefoot running. *Sports Biomech* 2021; doi: 10.1080/14763141.2020.1829021:1-14.

Table 1. Shoe characteristics, comfort, and experience. Data are mean ± standard deviation 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 to 12).

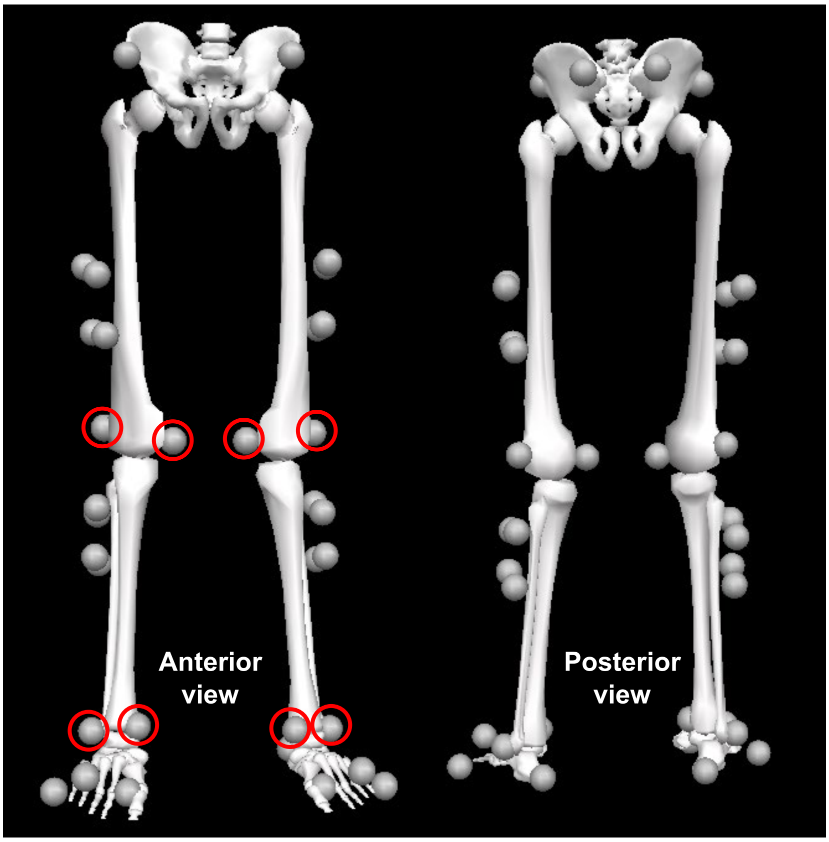


Figure 1. Marker placement for 3D motion capture of the runner. Anatomical reference markers on the runner were placed bilaterally on the: anterior and posterior superior iliac spines; medial and lateral femoral epicondyles; medial and lateral malleoli; and heel, 1st, 2nd, and 5th metatarsal heads. Tracking 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).

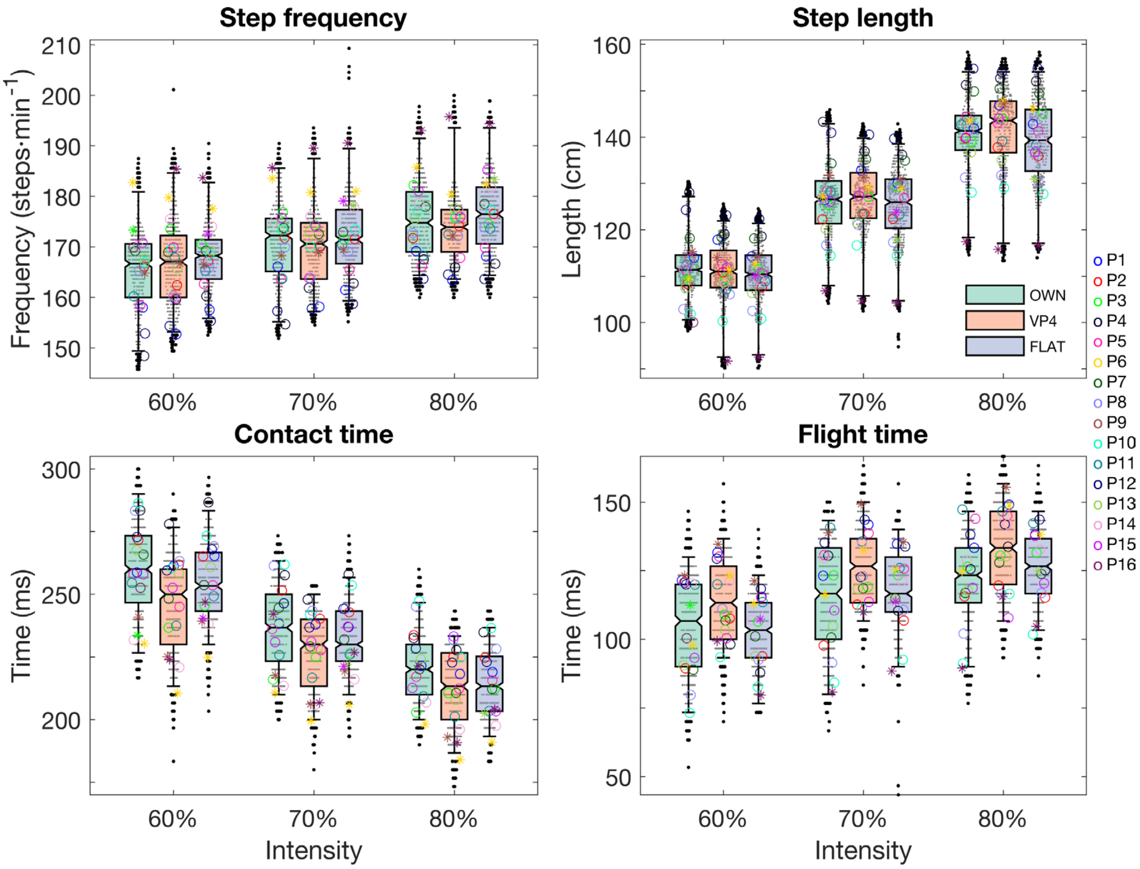


Figure 2. Boxplots of the spatiotemporal parameters extracted for each intensity (60%, 70%, and 80% of the speed that elicited VO_{2peak}) and footwear (OWN, VP4, and FLAT) condition. All data points are shown. Whiskers extend out above and below the median by 1.5 ∗ IQR, where IQR is the interquartile 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%.

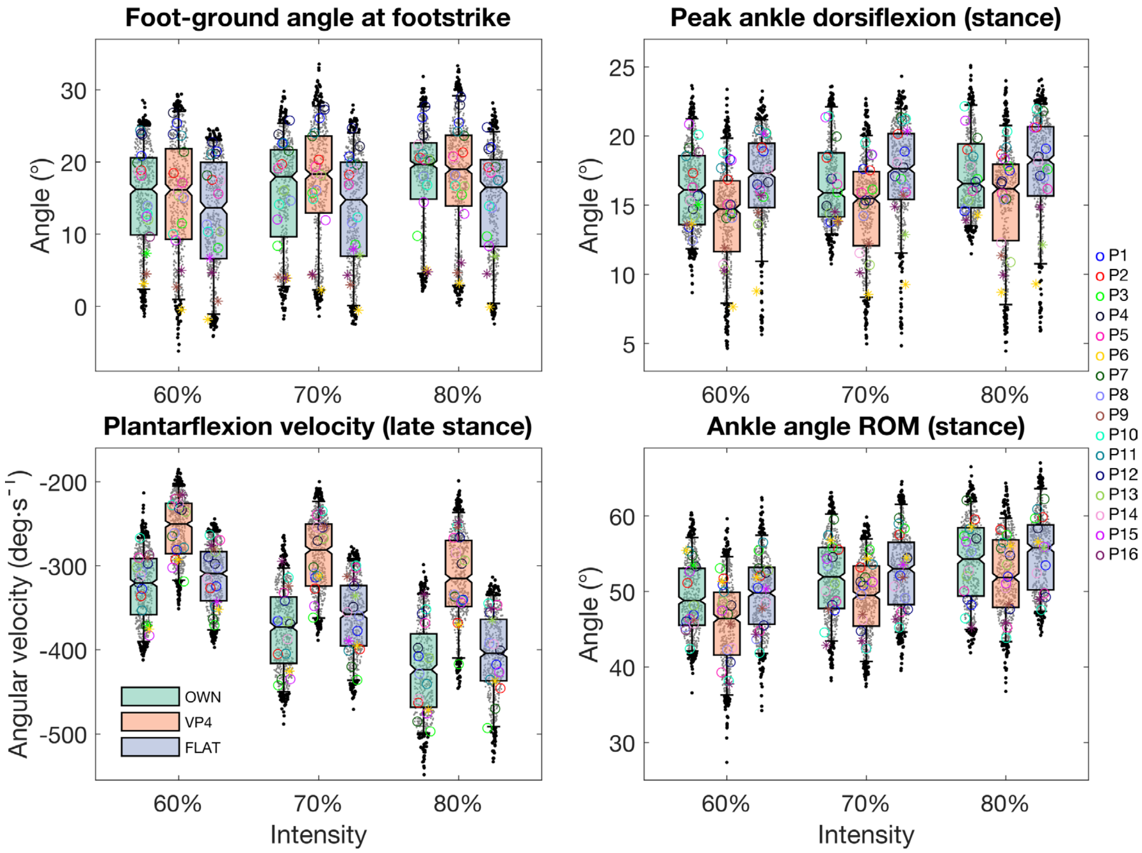


Figure 3. Boxplots of the kinematic parameters extracted at the foot and ankle for each intensity (60%, 70%, and 80% of the speed that elicited VO_{2peak}) and footwear (OWN, VP4, and FLAT) condition. All data points are shown. Whiskers extend out above and below the median by 1.5 ∗ IQR, where IQR is 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.

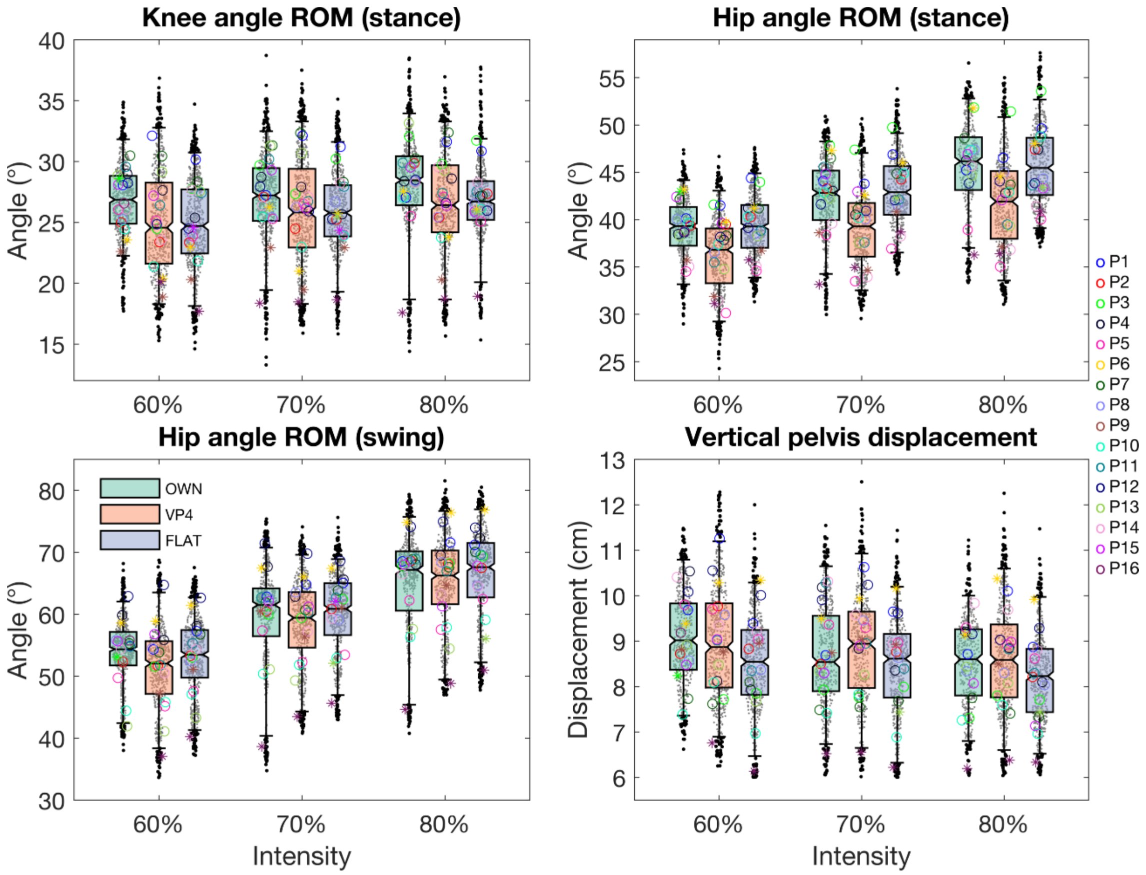


Figure 4. Boxplots of the kinematic parameters extracted at the knee, hip, and pelvis for each intensity (60%, 70%, and 80% of the speed that elicited VO_{2peak}) and footwear (OWN, VP4, and FLAT) condition. All data points are shown. Whiskers extend out above and below the median by 1.5 ∗ IQR, where 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.

Supplementary material

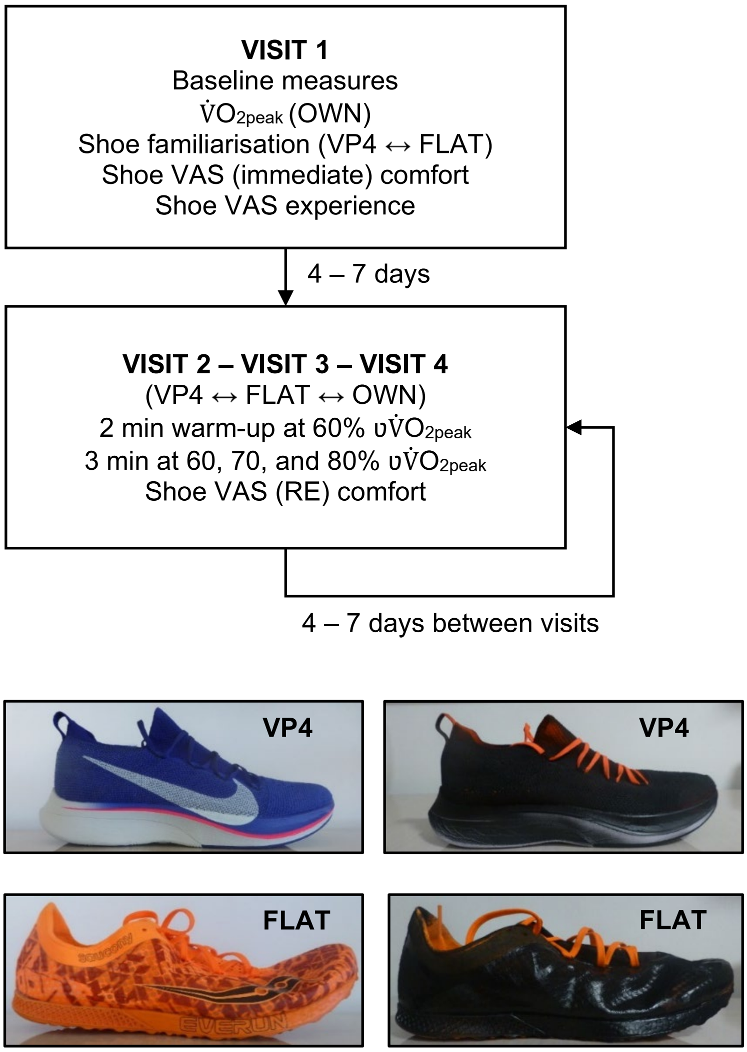
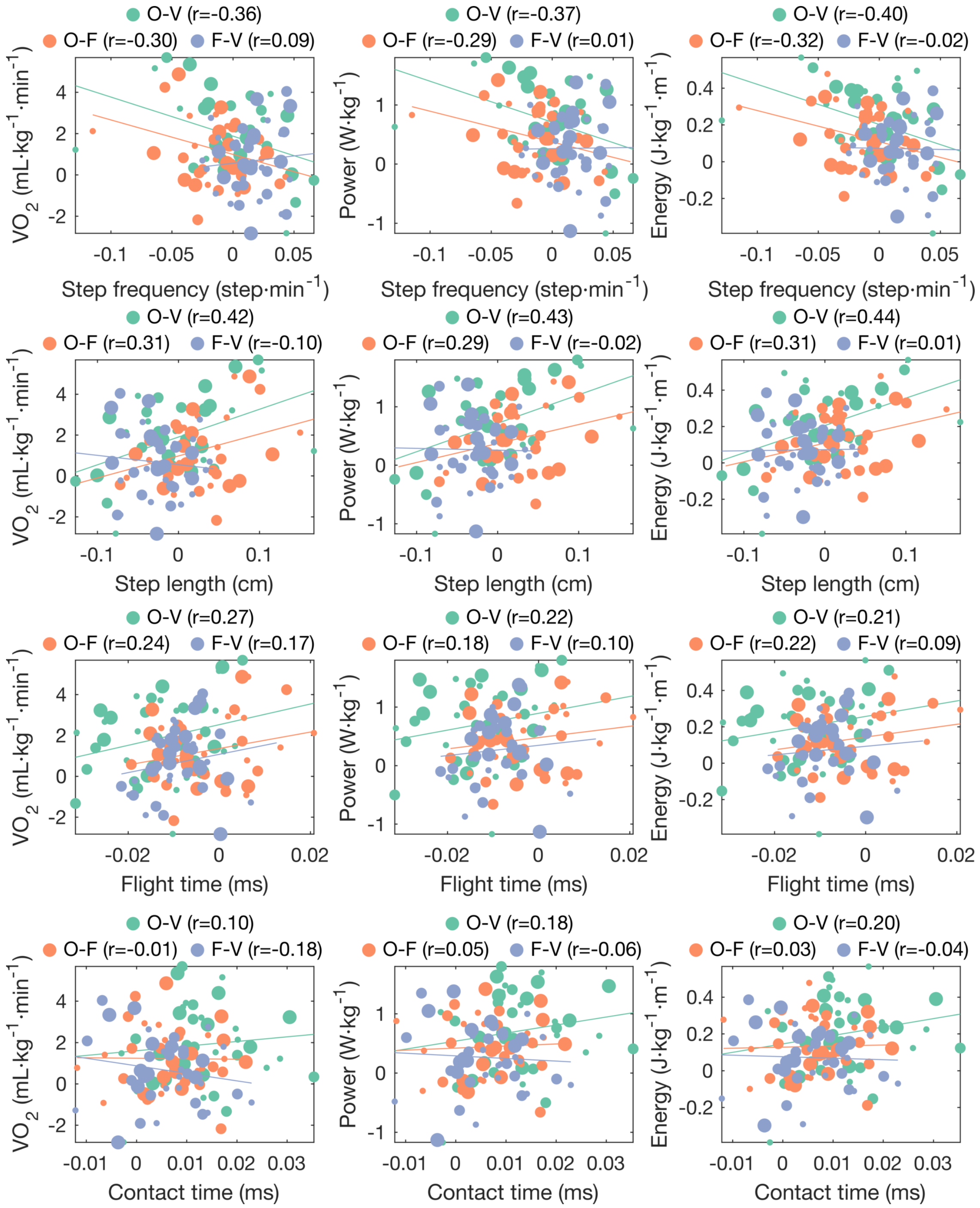
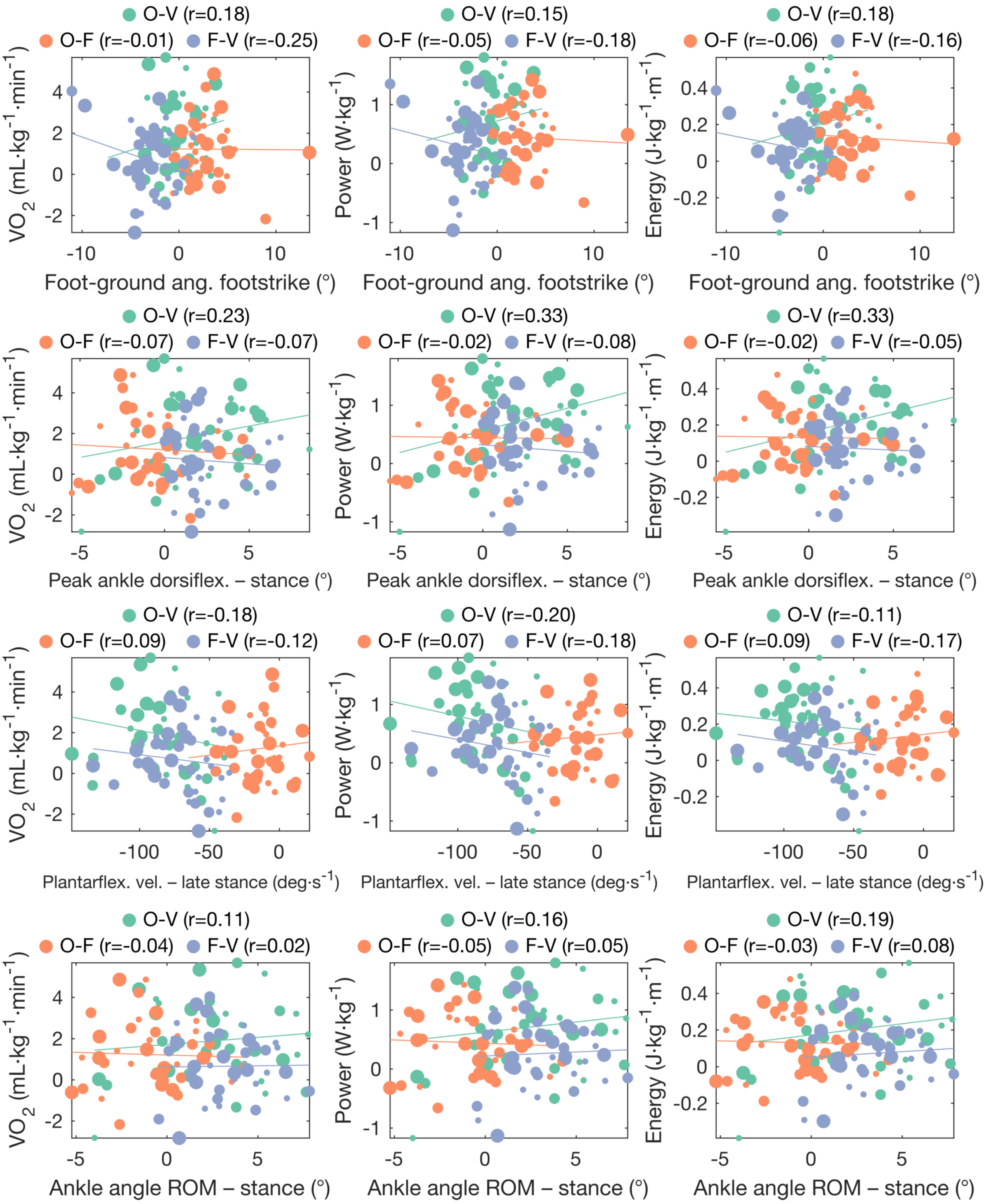


Figure S1. Experimental study design (top) and experimental footwear (bottom) pre and post being spray-painted black. ↔, randomised; FLAT, Saucony Endorphin Racer 2 racing flats; VP4, Nike Vaporfly; OWN, habitual shoes; RE, running economy; VAS, visual analogue scale; $\upsilon\dot{V}O_{2peak}$, speed that elicited $\dot{V}O_{2peak}$.

674 
O-V (r=-0.36)
O-F (r=-0.30) F-V (r=0.09)
O-V (r=-0.37)
O-F (r=-0.29) F-V (r=0.01)
O-V (r=-0.40)
O-F (r=-0.32) F-V (r=-0.02)
Step frequency (step·min-1)
O-V (r=0.42)
O-F (r=0.31) F-V (r=-0.10)
O-V (r=0.43)
O-F (r=0.29) F-V (r=-0.02)
O-V (r=0.44)
O-F (r=0.31) F-V (r=0.01)
Step length (cm)
O-V (r=0.27)
O-F (r=0.24) F-V (r=0.17)
O-V (r=0.22)
O-F (r=0.18) F-V (r=0.10)
O-V (r=0.21)
O-F (r=0.22) F-V (r=0.09)
Flight time (ms)
O-V (r=0.10)
O-F (r=-0.01) F-V (r=-0.18)
O-V (r=0.18)
O-F (r=0.05) F-V (r=-0.06)
O-V (r=0.20)
O-F (r=0.03) F-V (r=-0.04)
Contact time (ms)
VO2 (mL·kg-1·min-1)
Power (W·kg-1)
Energy (J·kg-1·m-1)


O-V (r=0.18)
O-F (r=-0.01) F-V (r=-0.25)
O-V (r=0.15)
O-F (r=-0.05) F-V (r=-0.18)
O-V (r=0.18)
O-F (r=-0.06) F-V (r=-0.16)
Foot-ground ang. footstrike (°)
O-V (r=0.23)
O-F (r=-0.07) F-V (r=-0.07)
O-V (r=0.33)
O-F (r=-0.02) F-V (r=-0.08)
O-V (r=0.33)
O-F (r=-0.02) F-V (r=-0.05)
Peak ankle dorsiflex. – stance (°)
O-V (r=-0.18)
O-F (r=0.09) F-V (r=-0.12)
O-V (r=-0.20)
O-F (r=0.07) F-V (r=-0.18)
O-V (r=-0.11)
O-F (r=0.09) F-V (r=-0.17)
Plantarflex. vel. – late stance (deg·s-1)
O-V (r=0.11)
O-F (r=-0.04) F-V (r=0.02)
O-V (r=0.16)
O-F (r=-0.05) F-V (r=0.05)
O-V (r=0.19)
O-F (r=-0.03) F-V (r=0.08)
Ankle angle ROM – stance (°)
VO2 (mL·kg-1·min-1)
Power (W·kg-1)
Energy (J·kg-1·m-1)

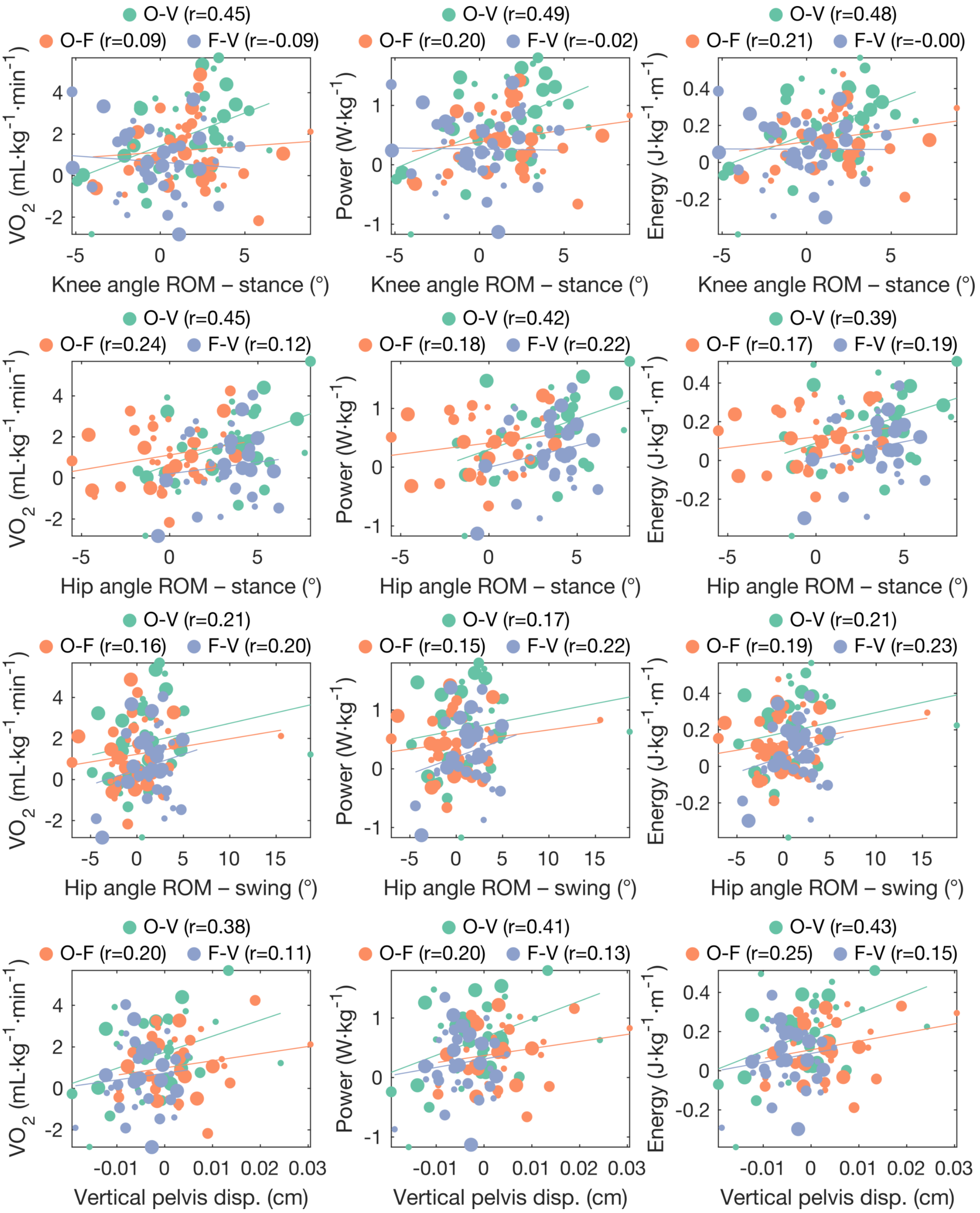


Figure S2. Scatterplots and Pearson correlation coefficients (*r*) of the differences in the mean kinematic values and running economy measures for each shoe comparison: OWN minus VP4 (O-V), OWN minus FLAT (O-F), and FLAT minus VP4 (F-V). Oxygen consumption (mL·kg^{-1}·min^{-1}), energy cost (W·kg^{-1}), and energetic cost of transport (J·kg^{-1}·m^{-1}) shown in the left, middle, and right columns, respectively. The size of the dot (small, medium, and large) indicates the intensity (60%, 70%, and 80% of the speed that elicited VO_{2peak}). OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%. ROM, range of motion. Disp., displacement.

Table S1. Median and interquartile ranges (IQR) of spatiotemporal and kinematic parameters from 40 steps of 16 male runners collected at 60%, 70%, and 80% of the speed that elicited VO_{2peak}.

Parameter	Shoe	Intensity					
		60%		70%		80%	
		Median	IQR	Median	IQR	Median	IQR
Step frequency (steps·min^{-1})	OWN	166.7	10.6	172.2	10.5	174.8	11.9
	VP4	167.1	12.2	170.6	11.1	173.9	8.3
	FLAT	168.2	7.8	171.4	10.7	176.5	11.2
Step length (cm)	OWN	111.4	6.5	126.6	9.2	141.3	7.4
	VP4	111.0	8.0	127.2	9.8	143.6	11.1
	FLAT	110.4	7.5	126.0	10.5	139.3	13.3
Flight time (ms)	OWN	106.7	30.0	116.7	33.3	123.3	20.0
	VP4	113.3	26.7	126.7	23.3	133.3	26.7
	FLAT	103.3	20.0	116.7	20.0	126.7	20.0
Contact time (ms)	OWN	260.0	26.7	236.7	26.7	220.0	20.0
	VP4	250.0	30.0	230.0	26.7	213.3	26.7
	FLAT	253.3	23.3	230.0	20.0	213.3	21.7
Foot-ground angle at FS (°)	OWN	16.2	10.7	17.9	12.0	19.6	7.8
	VP4	16.1	12.5	18.3	10.6	19.0	9.8
	FLAT	13.6	13.3	14.7	13.0	16.5	12.0
Peak ankle DF angle in stance (°)	OWN	16.1	5.0	15.9	4.6	16.6	4.6
	VP4	14.7	5.1	15.5	5.4	16.2	5.5
	FLAT	17.3	4.7	17.7	4.8	18.3	5.0
Plantarflexion velocity late stance (deg·s^{-1})	OWN	-320.6	66.6	-372.8	78.8	-423.6	87.1
	VP4	-250.4	59.8	-281.3	73.6	-315.1	78.5
	FLAT	-309.3	58.3	-357.7	71.6	-404.0	73.0
Ankle angle ROM in stance (°)	OWN	48.8	7.5	51.9	8.0	54.3	9.1
	VP4	46.4	8.3	49.5	8.0	51.8	8.9
	FLAT	49.8	7.5	53.0	8.2	55.8	8.6
Knee Angle ROM in stance (°)	OWN	26.9	3.9	27.2	4.3	28.5	4.0
	VP4	24.6	6.7	25.8	6.4	26.4	5.5
	FLAT	24.7	5.3	25.8	4.2	26.7	3.2
Hip Angle ROM in stance (°)	OWN	39.3	4.1	42.8	5.2	46.2	5.6
	VP4	36.8	5.8	39.3	5.7	42.0	7.2
	FLAT	39.3	4.5	42.9	5.1	45.5	6.1
Hip Angle ROM in swing (°)	OWN	54.4	5.4	61.5	7.7	67.2	9.6
	VP4	52.1	8.5	59.5	8.9	66.2	8.7
	FLAT	53.5	7.7	60.9	8.4	67.6	8.8
Vertical pelvis displacement (m)	OWN	9.0	1.5	8.5	1.7	8.6	1.5
	VP4	8.9	1.9	8.9	1.7	8.6	1.6
	FLAT	8.5	1.4	8.6	1.4	8.2	1.4

Notes. OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%. DF, dorsiflexion; FS, footstrike; ROM, range of motion.

Table S2. Differences in median values (Δ_{median}) of spatiotemporal and kinematic parameters from 40 steps of 16 male runners collected at 60%, 70%, and 80% of the speed that elicited VO_{2peak}.

Parameter	Intensity	OWN – VP4	OWN – FLAT	FLAT – VP4
Step frequency (steps·min^{-1})	60%	-0.4	-1.6	1.2
	70%	**1.6**	0.8	0.8
	80%	0.8	**-1.7**	**2.6**
Step length (cm)	60%	0.4	1.0	-0.6
	70%	-0.6	0.6	-1.2
	80%	**-2.2**	**2.0**	**-4.2**
Flight time (ms)	60%	**-6.7**	**3.3**	**-10.0**
	70%	**-10.0**	0.0	**-10.0**
	80%	**-10.0**	**-3.3**	**-6.7**
Contact time (ms)	60%	**10.0**	6.7	3.3
	70%	**6.7**	6.7	0.0
	80%	**6.7**	6.7	0.0
Foot-ground angle at FS (°)	60%	0.1	**2.6**	**-2.5**
	70%	-0.4	**3.2**	**-3.6**
	80%	0.7	**3.2**	**-2.5**
Peak ankle DF angle in stance (°)	60%	**1.4**	**-1.2**	**2.6**
	70%	0.4	**-1.8**	**2.2**
	80%	0.4	**-1.7**	**2.1**
Plantarflexion velocity late stance (deg·s^{-1})	60%	**-70.1**	**-11.3**	**-58.8**
	70%	**-91.5**	**-15.1**	**-76.4**
	80%	**-108.5**	**-19.5**	**-89.0**
Ankle angle ROM in stance (°)	60%	**2.4**	**-1.0**	**3.4**
	70%	**2.4**	**-1.1**	**3.5**
	80%	**2.4**	**-1.5**	**3.9**
Knee angle ROM in stance (°)	60%	**2.3**	2.2	0.1
	70%	**1.4**	1.4	0.0
	80%	2.0	1.7	0.3
Hip angle ROM in stance (°)	60%	**2.5**	0.0	**2.5**
	70%	**3.5**	-0.1	**3.6**
	80%	**4.2**	0.7	**3.5**
Hip angle ROM in swing (°)	60%	**2.3**	0.9	**1.4**
	70%	**2.1**	0.6	**1.4**
	80%	0.9	-0.5	**1.4**
Vertical pelvis displacement (cm)	60%	0.1	0.5	**-0.3**
	70%	**-0.4**	-0.1	**-0.3**
	80%	0.0	0.4	**-0.4**

Notes. Differences in medians between shoe types, according to notch values not overlapping, are shown in **bold**. OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%. DF, dorsiflexion; FS, footstrike; ROM, range of motion.

Table S3. Pearson correlation coefficients (*r*) with 95% confidence intervals [upper, lower] of the differences in the mean kinematic values and running economy measures for each shoe comparison.

Kinematic variable	Economy variable	OWN – VP4	OWN – FLAT	FLAT – VP4
Step frequency (steps·min^{-1})	VO_2 (mL·kg^{-1}·min^{-1})	**-0.36** [-0.60, -0.05]	**-0.30** [-0.56, 0.01]	0.09 [-0.23, 0.39]
	Power (W·kg^{-1})	**-0.37** [-0.61, -0.07]	-0.29 [-0.55, 0.02]	0.01 [-0.3, 0.32]
	Energy (J·kg^{-1}·m^{-1})	**-0.40** [-0.63, -0.10]	**-0.32** [-0.57, -0.01]	-0.02 [-0.33, 0.30]
Step length (cm)	VO_2 (mL·kg^{-1}·min^{-1})	**0.42** [0.12, 0.65]	**0.31** [0.00, 0.57]	-0.10 [-0.39, 0.22]
	Power (W·kg^{-1})	**0.43** [0.13, 0.65]	0.29 [-0.02, 0.55]	-0.02 [-0.33, 0.29]
	Energy (J·kg^{-1}·m^{-1})	**0.44** [0.15, 0.66]	**0.31** [0.00, 0.57]	0.01 [-0.30, 0.32]
Flight time (ms)	VO_2 (mL·kg^{-1}·min^{-1})	0.27 [-0.05, 0.53]	0.24 [-0.08, 0.51]	0.17 [-0.15, 0.46]
	Power (W·kg^{-1})	0.22 [-0.10, 0.49]	0.18 [-0.14, 0.46]	0.10 [-0.22, 0.40]
	Energy (J·kg^{-1}·m^{-1})	0.21 [-0.10, 0.49]	0.22 [-0.10, 0.50]	0.09 [-0.23, 0.39]
Contact time (ms)	VO_2 (mL·kg^{-1}·min^{-1})	0.10 [-0.22, 0.40]	-0.01 [-0.32, 0.30]	-0.18 [-0.46, 0.14]
	Power (W·kg^{-1})	0.18 [-0.14, 0.46]	0.05 [-0.27, 0.36]	-0.06 [-0.37, 0.26]
	Energy (J·kg^{-1}·m^{-1})	0.20 [-0.12, 0.48]	0.03 [-0.29, 0.34]	-0.04 [-0.35, 0.27]
Foot-ground angle at FS (°)	VO_2 (mL·kg^{-1}·min^{-1})	0.18 [-0.14, 0.46]	-0.01 [-0.32, 0.31]	-0.25 [-0.52, 0.07]
	Power (W·kg^{-1})	0.15 [-0.17, 0.44]	-0.05 [-0.35, 0.27]	-0.18 [-0.47, 0.13]
	Energy (J·kg^{-1}·m^{-1})	0.18 [-0.14, 0.46]	-0.06 [-0.36, 0.26]	-0.16 [-0.45, 0.16]
Peak ankle DF angle in stance (°)	VO_2 (mL·kg^{-1}·min^{-1})	0.23 [-0.08, 0.51]	-0.07 [-0.38, 0.24]	-0.07 [-0.38, 0.24]
	Power (W·kg^{-1})	**0.33** [0.02, 0.58]	-0.02 [-0.33, 0.29]	-0.08 [-0.38, 0.24]
	Energy (J·kg^{-1}·m^{-1})	**0.33** [0.02, 0.58]	-0.02 [-0.33, 0.29]	-0.05 [-0.35, 0.27]
Plantarflexion velocity late stance (deg·s^{-1})	VO_2 (mL·kg^{-1}·min^{-1})	-0.18 [-0.47, 0.14]	0.09 [-0.23, 0.39]	-0.12 [-0.42, 0.20]
	Power (W·kg^{-1})	-0.20 [-0.48, 0.12]	0.07 [-0.25, 0.37]	-0.18 [-0.47, 0.14]
	Energy (J·kg^{-1}·m^{-1})	-0.11 [-0.41, 0.21]	0.09 [-0.23, 0.39]	-0.17 [-0.45, 0.15]
Ankle angle ROM in stance (°)	VO_2 (mL·kg^{-1}·min^{-1})	0.11 [-0.21, 0.41]	-0.04 [-0.34, 0.28]	0.02 [-0.30, 0.33]
	Power (W·kg^{-1})	0.16 [-0.16, 0.45]	-0.05 [-0.36, 0.27]	0.05 [-0.26, 0.36]
	Energy (J·kg^{-1}·m^{-1})	0.19 [-0.13, 0.47]	-0.03 [-0.34, 0.28]	0.08 [-0.23, 0.38]
Knee angle ROM in stance (°)	VO_2 (mL·kg^{-1}·min^{-1})	**0.45** [0.16, 0.67]	0.09 [-0.23, 0.39]	-0.09 [-0.39, 0.23]
	Power (W·kg^{-1})	**0.49** [0.21, 0.69]	0.20 [-0.12, 0.48]	-0.02 [-0.33, 0.30]
	Energy (J·kg^{-1}·m^{-1})	**0.48** [0.20, 0.69]	0.21 [-0.11, 0.49]	0.00 [-0.32, 0.31]
Hip angle ROM in stance (°)	VO_2 (mL·kg^{-1}·min^{-1})	**0.45** [0.14, 0.68]	0.24 [-0.1, 0.53]	0.12 [-0.22, 0.43]
	Power (W·kg^{-1})	**0.42** [0.10, 0.65]	0.18 [-0.16, 0.48]	0.22 [-0.12, 0.51]
	Energy (J·kg^{-1}·m^{-1})	**0.39** [0.06, 0.63]	0.17 [-0.17, 0.48]	0.19 [-0.15, 0.48]
Hip angle ROM in swing (°)	VO_2 (mL·kg^{-1}·min^{-1})	0.21 [-0.11, 0.49]	0.16 [-0.16, 0.46]	0.20 [-0.13, 0.49]
	Power (W·kg^{-1})	0.17 [-0.15, 0.46]	0.15 [-0.18, 0.44]	0.22 [-0.10, 0.51]
	Energy (J·kg^{-1}·m^{-1})	0.21 [-0.11, 0.50]	0.19 [-0.13, 0.48]	0.23 [-0.10, 0.51]
Vertical pelvis displacement (cm)	VO_2 (mL·kg^{-1}·min^{-1})	**0.38** [0.06, 0.63]	0.20 [-0.15, 0.50]	0.11 [-0.23, 0.42]
	Power (W·kg^{-1})	**0.41** [0.09, 0.65]	0.20 [-0.15, 0.50]	0.13 [-0.20, 0.44]
	Energy (J·kg^{-1}·m^{-1})	**0.43** [0.12, 0.66]	0.25 [-0.10, 0.53]	0.15 [-0.19, 0.45]

Notes. Moderate correlations $|r| \geq 0.30$ are in **bold**. OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%. DF, dorsiflexion; FS, footstrike; ROM, range of motion; VO_2, oxygen consumption in mL·kg^{-1}·min^{-1}; Power, energy cost in W·kg^{-1}; Energy, energetic cost of transport in J·kg^{-1}·m^{-1}.

Table S4. Median and interquartile ranges (IQR) of physiological parameters of 16 male runners collected at 60%, 70%, and 80% of the speed that elicited VO_{2peak}.

Parameter	Shoe	Intensity					
		60%		70%		80%	
		Median	IQR	Median	IQR	Median	IQR
Oxygen consumption (mL·kg^{-1}·min^{-1})	OWN	34.3	3.0	39.6	5.0	46.0	4.0
	VP4	33.0	3.9	37.7	2.9	43.0	4.7
	FLAT	33.0	3.6	39.6	4.6	45.1	4.0
Energy cost (W·kg^{-1})	OWN	12.1	1.0	14.1	1.7	16.7	1.6
	VP4	11.5	1.3	13.6	1.1	15.4	1.6
	FLAT	11.7	1.3	13.9	1.8	16.1	1.3
Energetic cost of transport (J·kg^{-1}·m^{-1})	OWN	4.08	0.42	4.00	0.25	4.15	0.27
	VP4	3.90	0.66	3.88	0.37	3.92	0.21
	FLAT	3.89	0.47	3.89	0.34	4.06	0.31

Notes. OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%.

Table S5. Differences in median values (Δ_{median}) of physiological parameters from 16 male runners collected at 60%, 70%, and 80% of the speed that elicited VO_{2peak}.

Parameter	Intensity	OWN – VP4	OWN – FLAT	FLAT – VP4
Oxygen consumption ($mL \cdot kg^{-1} \cdot min^{-1}$)	60%	1.3	1.3	0.0
	70%	1.9	0.0	1.9
	80%	3.0	0.9	2.1
Energy cost ($W \cdot kg^{-1}$)	60%	0.6	0.4	0.2
	70%	0.5	0.1	0.4
	80%	1.3	0.5	0.7
Energetic cost of transport ($J \cdot kg^{-1} \cdot m^{-1}$)	60%	0.18	0.19	-0.01
	70%	0.12	0.11	0.00
	80%	0.24	0.10	0.14

Notes. OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%.