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Carbon-Plate Geometric Design for Performance: A Time-Series Kinematic Analysis of Asymmetry in Elite Marathoners

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Abstract

This study investigated how carbon-fiber plate curvature affects gait symmetry in elite long-distance runners. Although longitudinal bending stiffness is a known determinant of running economy, the symmetry implications of plate geometry remain unclear. Eighteen elite male marathon runners underwent 3D gait analysis using a Vicon system synchronized with AMTI force plates while wearing shoes with flat or curved carbon-fiber plates. Kinematic waveforms were assessed using SPM_1d, and discrete kinetics were quantified using the Symmetry Angle (SA). Plate geometry produced a symmetry trade-off, as the curved plate reduced SA for peak ankle eversion (p=0.014) and external rotation moments (p=0.016) and improved symmetry of hip rotational stiffness, whereas the flat plate better preserved symmetry in hip rotational angles and knee stiffness. Overall, curvature appears to modulate the kinetic chain by improving distal loading symmetry while potentially compromising proximal kinematic symmetry, providing design-relevant insights for balancing performance benefits with asymmetry-related injury risk.

Keywords: Carbon fiber plate, gait symmetry, biomechanics, marathon performance, injury

1 Introduction

The integration of carbon-fiber plates into the midsole of modern running footwear represents a paradigm shift in marathon performance and footwear biomechanics [1]. With high stiffness-to-weight ratios and the capacity to store and return elastic energy, these plates are intended to reduce mechanical energy losses at the metatarsophalangeal (MTP) joints, limit excessive MTP dorsiflexion, and improve the efficiency of the propulsive phase of the gait cycle [2]. In practice, the plate also interacts with compliant midsole foams to shape the shoe–foot system's overall deformation pattern, which can influence rollover dynamics, joint work distribution, and the timing of push-off. The performance benefits of this "super-shoe" technology was highlighted by the Breaking2 project, in which layered composite plate concepts were prominently discussed as part of a broader design strategy aimed at extending the limits of human endurance [3][4].

Existing research has largely emphasized the magnitude of longitudinal bending stiffness (LBS) and its relationship with running economy (RE), typically treating the plate as a stiffness element with a primarily sagittal-plane function [3]. However, the geometric profile of the plate, and particularly the contrast between a linear (flat) and a curvilinear (spoon-shaped) configuration, represents a critical yet under-examined design variable. The widely cited "teeter-totter" propulsion concept depends on the effective pivot point and lever behavior of the shoe–foot complex, both of which are strongly influenced by plate curvature and its interaction with midsole compression [2, 5]. A curved profile may better accommodate the foot's natural rocker mechanism and facilitate a smoother progression of the center of pressure (CoP), whereas a flatter profile may behave as a more rigid lever that alters rollover and necessitates compensatory adjustments across the kinetic chain [6].

Gait symmetry is increasingly viewed as a key biomarker of locomotor efficiency, neuromuscular control, and susceptibility to overuse injury [7]. Bilateral asymmetry in joint moments, stiffness, and segmental coordination can indicate unequal mechanical loading and is often discussed in relation to repetitive stress conditions such as tibial stress fractures and iliotibial band syndrome (ITBS) [8][9], especially when fatigue degrades motor control and shock attenuation strategies [10]. Although changes in shoe stiffness are known to influence step frequency, ground contact time, and joint-level work redistribution, the specific contribution of plate geometry to bilateral symmetry, and whether it differentially affects proximal versus distal joints, remains insufficiently understood [11].

This study aims to address this gap by quantifying the effects of flat versus curved carbon-fiber plate geometries on lower-limb symmetry in elite runners. By combining continuous time-series approaches using statistical parametric mapping (SPM) with discrete symmetry metrics, we test the hypothesis that plate geometry will differentially modulate proximal and distal joint mechanics across the stance phase. Establishing these relationships can provide a biomechanical basis for more targeted footwear design, in which curvature is treated as a controllable parameter to balance performance-oriented propulsion benefits with symmetry-related considerations that may be relevant for long-distance injury prevention.

2 Methods

2.1 Participants

Eighteen elite male marathon runners participated in this study (Age: 29.12 ± 3.40 years; Height: 1.74 ± 0.05 m; Weight: 69.05 ± 4.30 kg; BMI: 20.31 ± 2.36 kg/m²). Inclusion criteria required participants to be elite runners, defined as right-leg dominant, rearfoot strikers, with a personal best marathon time under 2 h 30 min. All participants were free of lower limb injuries for at least six months prior to data collection. The study protocol was approved by the Ethics Review Committee of Ningbo University (Approval No. TY2024077).

2.2 Experimental Footwear

This experiment utilized two pairs of running shoes: one pair equipped with a flat carbon-fiber plate and the other with a curved carbon-fiber plate. Both pairs were EU size 41 and appeared identical in appearance, differing solely in the shape of the embedded carbon plate in the midsole.

2.3 Experimental Protocol

Kinematic data were acquired using an eight-camera Vicon 3D motion capture system (200 Hz, Oxford, UK). Ground reaction forces (GRF) were simultaneously recorded using a 3D AMTI force platform (1000 Hz, Watertown, MA, USA). A standard 38-marker set was applied to anatomical landmarks including the sternum, pelvis, thigh, shank, and foot segments (Figure 1).Following a standardized treadmill warm-up, participants performed overground running trials along a 10-meter runway at a controlled speed of 18 km/h ± 5%. A valid trial was defined as one where the participant's left and right feet made full, sequential contact with independent force plates without gait alteration. Five valid trials were processed for each shoe condition.

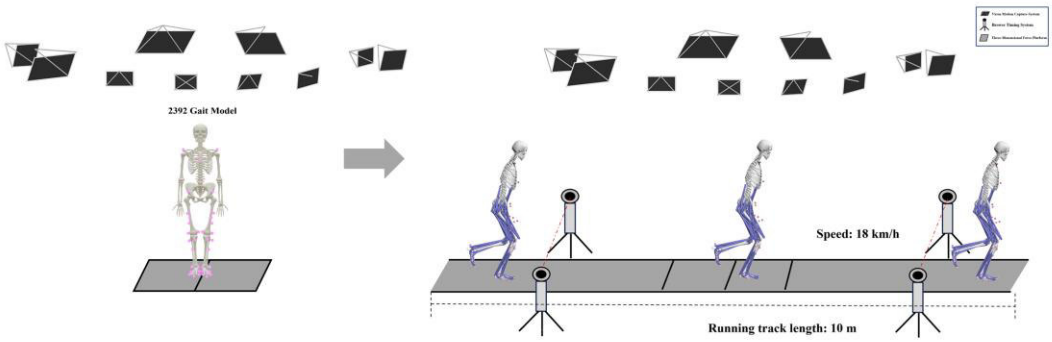

Figure 1. The left panel shows the static calibration setup, and the right panel illustrates the experimental setup for collecting kinematic and kinetic data during running and standing phases.

2.4 Data Processing and Statistical Analysis

Visual 3D 6.0 (C-Motion Inc., USA) was employed for data processing. Joint angles and internal joint moments (normalized to body mass) were computed via inverse dynamics.

Symmetry between the left and right sides was assessed using the symmetry angle (SA) based on discrete data points. This metric is based on the angle formed by the vector connecting the left and right values in a coordinate system:

$$SA = \frac{\left(45^{\circ} - \arctan\left(\frac{X_{left}}{X_{right}}\right)\right)}{90^{\circ}} \times 100\% \tag{1}$$

Joint stiffness is related to injury and performance, and is defined as follows:

$$K_{joint} = \frac{\Delta M}{ROM} \tag{2}$$

Here, Δ M is defined as the change in joint moment of the ankle, knee, and hip during the stance phase, and ROM is defined as the joint range of motion during the stance phase.

Statistical analysis was performed using two complementary approaches. For the time-series analysis, one-dimensional Statistical Parametric Mapping (SPM_1d) in MATLAB R2022a was used to compare continuous joint angle waveforms throughout the stance phase, with statistical significance set at $p < 0.05$. For the discrete analysis, a two-way ANOVA was conducted to compare peak moments and stiffness across Limb (Left/Right) and Shoe (Flat/Curved), and paired t-tests were used to examine differences in SA values between shoe conditions.

3 Results

3.1 Kinematic Analysis

The SPM analysis revealed distinct, phase-specific bilateral asymmetry patterns that depended on plate geometry. As shown in Figure 2, under the flat carbon plate condition, significant asymmetry occurred in hip flexion during early stance (0–18%, p=0.043), with greater flexion on the left side, while knee extension asymmetry was evident in both early (0–11%) and late stance (29–100%) phases; additionally, the right ankle showed significantly greater dorsiflexion across mid-to-late stance (12–87%, p=0.001) and greater external rotation in late stance (70–95%, p=0.029). As shown in Figure 3, in contrast, under the curved carbon plate condition, the temporal profile of asymmetry shifted, with hip flexion asymmetry emerging later in stance (27–100%, p=0.001), the right knee maintaining greater extension from mid-to-late stance (35–100%, p=0.001), and ankle asymmetry being more confined, appearing as plantarflexion differences in late stance (74–89%) and external rotation differences in early stance (0–13%).

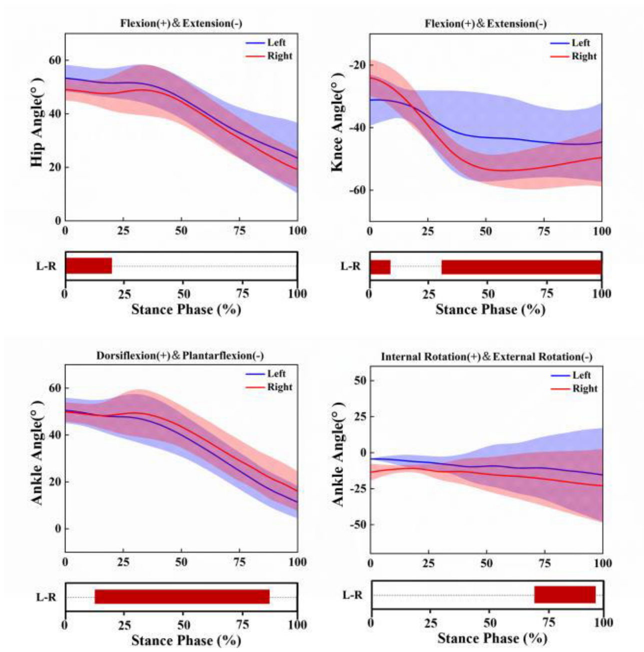

Figure 2. SPM_1d analysis of joint angle variations during the stance phase in the flat carbon plate shoe condition. Left: left lower limb; Right: right lower limb. Significant differences are shown.

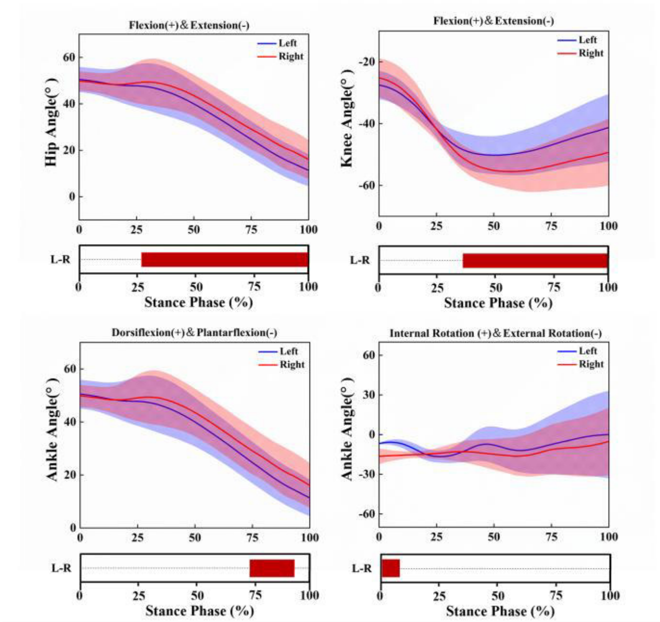

Figure 3. SPM_1d analysis of joint angle variations during the stance phase in the curved carbon plate shoe condition. Left: left lower limb; Right: right lower limb. Significant differences are shown.

3.2 Kinetic Analysis

Table 1 summarizes peak joint moments and stiffness across conditions. Significant Shoe × time × Limb interactions were found for ankle sagittal stiffness (p=0.001), knee frontal stiffness (p=0.018), and hip transverse stiffness (p=0.018), indicating limb- and time-dependent effects of plate geometry. Under the flat plate condition, ankle sagittal stiffness was notably higher on the left than the right (9.75 vs. 6.12 Nm/deg), whereas this asymmetry was largely reduced with the curved plate (6.26 vs. 6.70 Nm/deg), suggesting a homogenizing effect on distal stiffness between limbs.

1. table Bilateral Joint Moments and Stiffness (Selected Significant Variables)

Variable	Flat Plate (L / R)	Curved Plate (L / R)	Shoe × Limb (p)
Ankle Sagittal Stiffness (Nm/deg)	9.75 / 6.12	6.26 / 6.70	0.001*
Knee Frontal Moment (Nm/kg)	-1.13 / -0.79	-0.89 / -0.99	0.001*
Hip Transverse Stiffness (Nm/deg)	4.98 / 2.89	2.32 / 4.14	0.018*

Note: Data presented as Mean. * indicates statistical significance (p < 0.05). L: left lower limb; R: right lower limb.

3.3 Symmetry Analysis

Table 2 presents the comparison of Symmetry Angles (SA), indicating that plate geometry exerted joint-specific and segment-dependent effects on bilateral symmetry across the lower limb, suggesting that the response was not uniform along the kinetic chain. At the ankle, the curved plate produced a clear improvement in symmetry for key kinetic variables, with SA decreasing by 2.94%

for peak eversion moments (p=0.014) and by 12.27% for external rotation moments (p=0.016), which together indicate a more balanced frontal- and transverse-plane loading pattern between limbs. In contrast, this distal kinetic benefit was accompanied by a small but significant deterioration in kinematic symmetry for rotational angles, as reflected by a 2.7% increase in SA (p=0.046), implying that joint rotation may have been controlled differently across limbs despite more symmetric moment profiles.

At the knee, the curved plate also tended to enhance symmetry in both kinematic and kinetic outcomes, as shown by a 4.56% reduction in SA for flexion–extension angles (p=0.029) and a 2.94% reduction in SA for peak frontal plane moments (p=0.003), suggesting improved inter-limb consistency in sagittal-plane motion and transverse-plane loading. However, sagittal-plane stiffness became more asymmetrical under the curved plate, with SA increasing by 4.2% (p=0.008), which may reflect divergent limb-specific strategies for impact attenuation and energy storage during stance.

At the hip, a different pattern emerged, with the flat plate proving more effective in preserving rotational angle symmetry (p=0.028), indicating comparatively better proximal kinematic alignment between limbs. Nevertheless, the curved plate still conferred symmetry benefits in selected hip kinetics, improving symmetry for peak flexion–extension moments (p=0.037) and rotational stiffness (p=0.033). Collectively, these findings support the notion that plate curvature may preferentially reduce asymmetry in distal joint loading while inducing more complex, and sometimes opposing, changes in proximal kinematics and stiffness-related behavior.

2. table Summary of Significant Effects of Plate Geometry on Kinematic, Kinetic, and Stiffness Symmetry of Ankle, Knee, and Hip Joints

Joint	Variable	Plane	Flat (Mean ± SD)	Curved (Mean ± SD)	Sig. (p)	ES(Cohen's d)
Ankle	Joint Moment	Frontal	5.61 (4.18)	2.67 (1.48)	0.014*	0.571
	Joint Moment	Horizontal	25.32 (11.25)	13.05 (7.73)	0.016*	0.556
	Joint Angle	Horizontal	22.67 (4.51)	25.37 (6.76)	0.046*	-0.452
Knee	Joint Angle	Sagittal	10.77 (7.40)	6.21 (5.19)	0.029*	0.501
	Joint Moment	Frontal	9.42 (5.12)	5.77 (4.32)	0.003*	0.71
	Joint Stiffness	Sagittal	20.62 (12.42)	24.82 (8.64)	0.008*	-0.622
Hip	Joint Angle	Horizontal	11.32 (9.25)	14.05 (6.43)	0.028*	-0.502
	Joint Moment	Sagittal	9.68 (4.12)	5.15 (4.32)	0.037*	0.475
	Joint Stiffness	Horizontal	12.13 (8.73)	8.37 (7.11)	0.033*	0.485

4 Discussion

This study provides the first systematic evidence that carbon-fiber plate geometry can act as a kinetic regulator and differentially shape lower-limb asymmetry in elite marathon runners. Importantly, the present findings suggest that plate curvature should not be viewed solely as a performance-oriented feature, but also as a design variable capable of redistributing mechanical demands across joints and limbs, thereby altering the symmetry profile of the running gait [12].

The curved carbon plate showed a clear advantage in improving ankle joint symmetry, particularly for torsional moments and sagittal-plane stiffness. Its spoon-shaped profile appears to better match the foot's natural rocker function during stance and may facilitate a smoother rollover and more consistent lever behavior at push-off. This geometric conformity likely supports a more consistent and symmetrical center-of-pressure progression, which in turn may reduce the compensatory stabilization demands on the ankle evertors and invertors and lower the need for limb-specific control strategies to maintain mediolateral stability [13]. The 12.27% reduction in SA for ankle external rotation moments is clinically meaningful because torsional asymmetry has been recognized as a risk factor for tibial stress injuries, and a more balanced transverse-plane loading pattern may help attenuate cumulative asymmetric stress over prolonged running exposure. Notably, the finding that kinetic symmetry improved despite a small deterioration in rotational angle symmetry suggests that curvature may preferentially regulate loading rather than kinematics, highlighting a potential dissociation between motion symmetry and load symmetry at the ankle [14].

Although the curved plate improved distal mechanics, it also amplified hip-level asymmetry, most notably in rotational angles, whereas the flat plate maintained better proximal symmetry [15]. One possible explanation is that the flat plate provides a more rigid and predictable base of support, thereby lowering the neuromuscular demand on the hip rotators to control limb orientation and stabilizing the proximal segments through a more consistent foot–ground interaction. By contrast, the curved plate may enhance propulsion but also introduce greater forward translation, faster rollover, or reduced “settling time” during stance, which could require the dominant and non-dominant hips to respond differently and ultimately increase kinematic asymmetry. This proximal trade-off is consistent with the concept of kinetic-chain interdependence, in which changes that benefit distal loading patterns may be offset by greater variability or asymmetry in proximal control [16]. From an applied perspective, these results imply that runners with limited hip rotational control, prior hip-related symptoms, or pronounced baseline asymmetry may respond differently to curved plates than runners with robust proximal stability, suggesting the need for individualized footwear selection or adaptation periods.

The interaction effects observed for stiffness in Table 1 are particularly informative. Under the flat plate condition, ankle stiffness was markedly more asymmetrical, suggesting that the non-dominant limb adopted a stiffening strategy to manage impact loading, whereas the curved plate tended to homogenize this response [17]. Such stiffening can be interpreted as a limb-specific strategy to control joint excursion and stabilize the ankle during early-to-mid stance, potentially at the cost of higher localized mechanical demand on the plantar flexor–Achilles complex. Because stiffness asymmetry has been associated with unilateral fatigue and injury risk, the curved plate may provide a protective benefit over marathon distances by equalizing mechanical demands on the plantar flexors and reducing the likelihood that one limb disproportionately accumulates fatigue-related load [8][18][19]. At the same time, the observed stiffness-related changes reinforce that symmetry outcomes are not uniformly improved by curvature, and that the “optimal” plate geometry may depend on whether the design goal prioritizes distal load equalization, proximal kinematic stability, or a balanced compromise between the two.

5 Conclusion

The geometric profile of carbon-fiber plates in running shoes can substantially modulate lower-limb biomechanical symmetry. Curved plates tend to promote better symmetry at the ankle and in knee joint moments, while flat plates are superior for preserving symmetry in knee sagittal-plane stiffness and hip rotational angles. In contrast, flat plates appear to favor symmetry in proximal joint kinematics, especially hip rotation, and may provide a more stable platform for pelvic control. These findings suggest that no single plate geometry is universally optimal, and footwear design should treat curvature as a tunable variable to balance propulsion-related benefits with kinetic-chain symmetry, with curved plates potentially better for reducing distal loading asymmetries and flat plates potentially better for runners who require greater proximal stability. Future work should evaluate these effects across the full duration of a marathon to determine whether the symmetry benefits of curved plates persist under fatigue.

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