

## **Energetics and biomechanics of running footwear with increased longitudinal bending stiffness: a narrative review**

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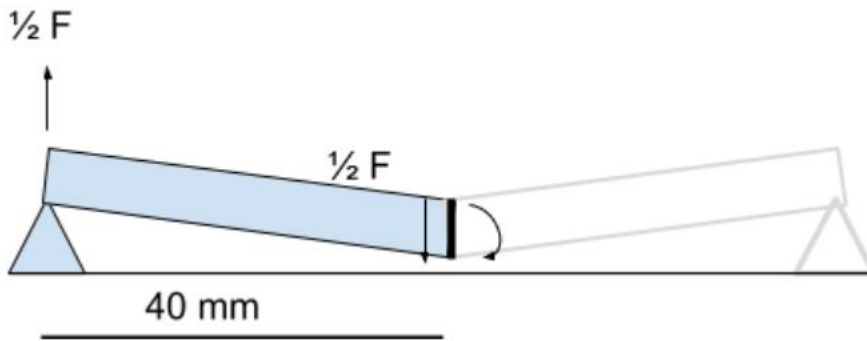
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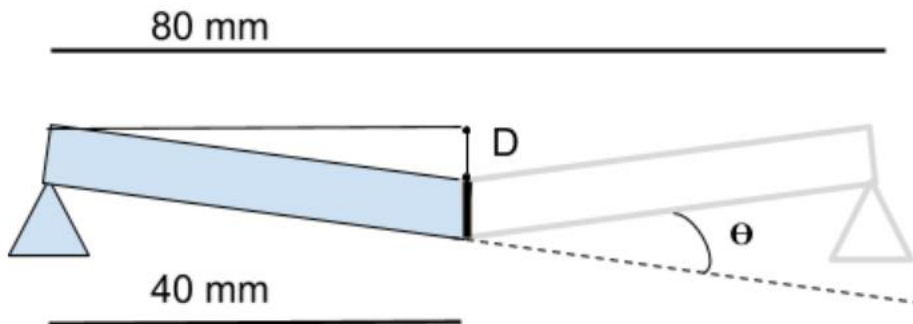
## **Electronic Supplementary Material Appendix S1**

To allow direct comparison of stiffness values between studies, we converted all the reported values to Nm/rad. All the studies included in this review that reported stiffness values in N/mm (or kN/m) determined these values using a standard three-point bending test with support 80 mm apart. We converted the applied force (F) to the applied torque (T) based on the simplified diagram below which shows that

$$T = \frac{1}{2} F * 40 \text{ mm} = \frac{1}{2} F * 0.04 \text{ m}.$$



Next, we converted the displacement (D) measured in mm to a rotation ( $\theta$ ) in radians, based on the diagram below which shows that  $\theta = 2 \tan^{-1}(D/40)$



Therefore, from these two conversions:

Bending stiffness (Nm/rad)

$$= T/\theta = (\frac{1}{2} F * 0.04)/(2 \tan^{-1}(D/40)) = (F * 0.04)/(4 \tan^{-1}(D/40))$$

With applied force F in N and the measured displacement D in mm. Given the bending stiffness is in N/mm, we set the value of F to be equal to the bending stiffness value such that D is 1 mm. Under this assumption:

$$\text{Bending stiffness (Nm/rad)} = (F_{1\text{mm}} * 0.04)/(4 \tan^{-1}(1/40)) = F_{1\text{mm}} * 0.4001$$

with  $F_{1\text{mm}}$  is equal to the value of the bending stiffness (N/mm). It should be noted that force-deformation curves often show nonlinear behavior and hence local linearized stiffness values depend on measurement range. Since measurement range was not standardized between studies, these converted values in Table 1 should not be compared directly between studies that used different measurement ranges.

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### **Conflicts of interest / Competing interests**

Wouter Hoogkamer has received research grants from Puma North America. Justin Ortega, Laura Healey and Wannes Swinnen declare that they have no potential conflicts of interest relevant to the content of this review.

### **Data availability**

All data discussed in this manuscript are provided in the tables.

### **Authors' contributions**

Conceptualization: Wouter Hoogkamer; Literature search: Justin A. Ortega, Laura Healey, Wannes Swinnen; Writing - original draft preparation: Justin A. Ortega, Laura Healey, Wannes Swinnen, Wouter Hoogkamer; Writing - review and editing: Justin A. Ortega, Laura Healey, Wannes Swinnen, Wouter Hoogkamer

**Table S1** Overview of the longitudinal bending stiffness assessment specifics of the articles discussed in the current review.

Study	Setup	Displacement Range	Measurement Range	Loading Rate	Cycles	Shoe Condition	Experimental Bending Stiffness	Bending Stiffness (Nm/rad)	Shoe Mass (g)	Placement
Roy & Stefanyshyn 2006 [18]	3 Point Bending Test	0 to 7.5 mm	5 to 6 mm	75 mm/s	20	Adidas Adistar Comp	18 N/mm	7.2	242	Embedded in midsole
						+ CF plate	38 N/mm	15.2	237	
						+ thicker CF plate	45 N/mm	18.0	240	
Willwacher et al 2013 [31]	3 Point Bending Test	0 to 7.5 mm	5 to 6 mm	15 mm/s	5 x 20	Nike Free 3.0	0.65 - 0.76 N/mm	0.3 - 0.3	not reported	Insole
						+ 0.9 mm CF plate	5.29 - 7.11 N/mm	2.1 - 2.8		
						+ 3.2 mm CF plate	16.16 - 17.10 N/mm	6.5 - 6.8		
Willwacher et al 2014 [29]	3 Point Bending Test	0 to 7.5 mm	5 to 6 mm	15 mm/s	5 x 20	Nike Free 3.0	0.76 ± 0.01 N/mm	0.3	not reported	Insole
						+ 0.9 mm CF plate	7.11 ± 0.22 N/mm	2.8		
						+ 3.2 mm CF plate	16.16 ± 0.20 N/mm	6.5		
Madden et al 2016 [19]	3 Point Bending Test	0 to 7.5 mm	5 to 6 mm	75 mm/s	20	Adidas PT	8.1 N/mm	3.2	135	Within outsole, forefoot & midfoot
						Adidas PT + CF stiffening plates	23.1 N/mm	9.2	162	
Takahashi et al 2016 [49]	3 Point Bending Test	5 to 10 mm	5 to 10 mm	15 mm/s	20	Barefoot	-	-	not controlled	Insole
						New Balance 1400	14.8 ± 0.5 N/mm	5.9		
						+ 0.8 mm CF plate	22.5 ± 0.5 N/mm	9.0		
						+ 1.6 mm CF plate	28.7 ± 0.8 N/mm	11.5		
Willwacher et al 2016 [32]	3 Point Bending Test	0 to 7.5 mm	5 to 6 mm	15mm/s	5 x 20	Brooks Pure Connect	1.44 ± 0.03 N/mm	0.6	control	Insole
						+ Plastic plate	13.92 ± 0.08 N/mm	5.6		
						+ Fiberglass plate	21.82 ± 0.21 N/mm	8.7		
Oh & Park 2017 [20]	3 Point Bending Test	0 to 0.5 rad	0 to 0.5 rad	8.3 mm/s	not reported	Reebok ZQUICK	1.5 Nm/rad	1.5	control	Insole
						+ 0.8 mm CF plate	10.0 Nm/rad	10.0		
						+ 1.2 mm CF plate	24.5 Nm/rad	24.5		
						+ 1.5 mm CF plate	32.1 Nm/rad	32.1		
						+ 1.8 mm CF plate	42.1 Nm/rad	42.1		
Flores et al 2019 [21]	3 Point Bending Test	7.5 mm	5 to 6 mm	15 mm/s	not reported	+ 2.0 mm CF plate (n =1)	56.6 Nm/rad	56.6	+ 52	
						Kalenji PU PT	15.4 ± 1.0 N/mm	6.2		
						Kalenji EVA PT	19.2 ± 1.0 N/mm	7.7		
						Kalenji PU PT + 0.9 mm CF plate	38.0 ± 1.8 N/mm	15.2		
Hoogkamer et al 2019 [10]	Rotational Axis Machine Test	30 degrees	27 degrees	24 deg/s	20	Kalenji EVA PT + 0.9 mm CF plate	43.2 ± 2.0 N/mm	17.3	367	Underneath insole, forefoot & midfoot
						Adidas Adizero Adios Boost 2	7.0 Nm/rad	7.0		
						Nike Zoom Streak 6	9.4 Nm/rad	9.4		
Cigoja et al 2019 [30]	3 Point Bending Test (160mm spacing)	15 mm	80-90% of the loading curve	10 mm/s	10	Nike Vaporfly PT (curved CF plate)	18.5 Nm/rad	18.5	250	Embedded in midsole
						Nike Free 5.0	1.2 N/mm	1.9		
						+ CF plate	11.9 N/mm	19.0		
Day & Hahn 2019 [24]	Custom set up	Not reported	Not reported	Not reported	3	Epic React Flyknit	5.9 Nm/rad	5.9	239	Underneath insole
						+ 3 mm Nylon 11 plate	10.5 Nm/rad	10.5		
						+ 2x 3 mm Nylon plate	17.0 Nm/rad	17.0		
Flores et al 2019 [34]	Exeter Research flex tester	30 degrees	10 to 30 degrees	360 deg/s	30	Kalenji PT + top loaded CF plate	0.26 ± 0.02 Nm/deg	14.9	403.2	Insole vs. between midsole and outsole
						Kalenji PT + bottom loaded CF plate	0.28 ± 0.01 Nm/deg	16.0		
McLeod et al 2020 [22]	3 Point Bending Test	7.5 mm	5 to 6 mm	16 mm/s	5	Saucony Freedom	8.3 - 10.0 N/mm	3.3 - 4.0	280 - 299	Embedded between midsole and outsole, forefoot & midfoot
						CF plates with increasing stiffness	11.3 - 14.2 N/mm	4.5 - 5.7		
							13.0 - 15.4 N/mm	5.2 - 6.2		
							14.6 - 18.0 N/mm	5.8 - 7.2		
							16.3 - 25.6 N/mm	6.5 - 10.2		
							21.9 - 26.2 N/mm	8.8 - 10.5		
Beck et al 2020 [23]	3 Point Bending Test	10 mm	5 to 9 mm	8 mm/s	3	Adidas Adizero Adios Boost 2	13.0 ± 1.0 N/mm	5.2	controlled	Insole
						+ 0.8 mm CF plate	31.0 ± 1.5 N/mm	12.4		
						+ 1.6 mm CF plate	43.1 ± 1.6 N/mm	17.2		
						+ 3.2 mm CF plate	84.1 ± 1.1 N/mm	33.6		
Cigoja et al 2020 [48]	3 Point Bending Test (160mm spacing)	15 mm	80-90% of the loading curve	10 mm/s	10	Nike Free 2018 + CF plate	1.69 N/mm 13.44 N/mm	2.7 21.5	not reported	Underneath insole

CF: carbon fiber; EVA: ethylene-vinyl acetate; PT: prototype; PU: polyurethane

**Table S2** Running economy outcomes for different longitudinal bending stiffness footwear interventions.

Study	Shoe Condition	Bending Stiffness (Nm/rad)	Participants	Velocity (m/s)	Running Economy			RE % change (for significant comparisons)	EMG (= no significant difference)	Participant Running Level
Roy & Stefanyshyn 2006 [18]	Adidas Adistar Comp + CF plate + thicker CF plate	7.2	13	3.7 average (based on VO2max)	(ml/kg/min)			stiff vs. control: 0.80%	soleus ≈ gastrocnemius ≈ biceps femoris ≈ vastus lateralis ≈ rectus femoris ≈	≤ 40 min for 10-km race ≥ 25 km/week
		15.2			45.323 ± 3.032					
		18.0			44.960 ± 3.002					
					45.246 ± 3.125					
Madden et al 2016 [19]	Adidas PT Adidas PT + CF stiffening plates	3.2	18 men	3.2 ± 0.5 (based on VO2max)	(ml/kg/min)			For responders: stiff vs. control: 3.06%	-	Recreational athletes
		9.2			38.1 (R: 35.9, NR: 40.4) 37.7 (R: 34.8, NR: 40.8)					
Oh & Park 2017 [20]	Reebok ZQUICK + 0.8 mm CF plate + 1.2 mm CF plate + 1.5 mm CF plate + 1.8 mm CF plate + 2.0 mm CF plate (n =1)	1.5	19	2.43 ± 0.23 (based on VO2max)	Overall similar [reported in graph only]			k <sub>cr</sub> vs. control and stiffest: 1.1 ± 1.2%	-	Recreational athletes
		10.0								
		24.5								
		32.1								
		42.1								
		56.6								
Flores et al 2019 [21]	Kalenji PU PT Kalenji EVA PT Kalenji PU PT + 0.9 mm CF plate Kalenji EVA PT + 0.9 mm CF plate	6.2	19 men	3.0 ± 0.31 (90% of VAT)	(kJ/kg/km)			no significant differences	-	Recreational runners
		7.7			4.73 ± 0.51					
		15.2			4.75 ± 0.50					
		17.3			4.76 ± 0.51					
					4.72 ± 0.49					
Hoogkamer et al 2018 [5]	Adidas Adizero Adios Boost 2 Nike Zoom Streak 6 Nike Vaporfly PT (curved CF plate)	7.0	18 men	3.89, 4.44, 5.00	(W/kg)	(W/kg)	(W/kg)	Overall across all velocities: NVF vs. NS: 4.16% NVF vs. AB: 4.01%	-	≤ 32 min for 10-km race or equivalent
		9.4			14.13 ± 0.84	17.03 ± 1.02	20.25 ± 1.18			
		18.5			14.17 ± 0.82	17.07 ± 1.02	20.26 ± 1.06			
Barnes & Kilding 2019 [8]	Nike Zoom Matumbo 3 Adidas Adizero Adios Boost 3 Nike Vaporfly Nike Vaporfly+ (mass matched to AB)	<7.0 7.0 18.5 18.5	12 men	3.89, 4.44, 5.00	(W/kg)	(W/kg)	(W/kg)	Overall across all velocities: NVF vs. AB: 4.2 ± 1.2% NVF vs. NZM: 2.6 ± 1.3% NVF+ vs. AB: 2.9 ± 1.3%	-	≤ 15 min for 5-km race or ≤ 30 min for 10-km race or equivalent
					15.71 ± 0.76	18.39 ± 0.87	21.49 ± 1.36			
					15.85 ± 0.71	18.81 ± 0.91	21.74 ± 1.19			
					15.25 ± 0.71	17.99 ± 0.88	20.86 ± 1.30			
					15.50 ± 0.63	18.15 ± 0.91	21.14 ± 1.21			
		15.46 ± 0.92 15.54 ± 0.95 15.01 ± 0.91 15.21 ± 0.95	12 women	3.89, 4.17, 4.44					-	≤ 17:15 min for 5-km race ≤ 35:30 min for 10-km race or equivalent
						16.86 ± 1.13	18.60 ± 0.85			
						17.05 ± 1.06	18.88 ± 0.86			
						16.55 ± 1.03	18.24 ± 0.82			
						16.67 ± 1.06	18.43 ± 0.80			
Hunter et al 2019 [9]	Adidas Adizero Adios Boost 3 Nike Zoom Streak 6 Nike Vaporfly	7.0	19 men	4.44	(ml/kg/min)			NVF vs. AB: 2.8% NVF vs. NS: 1.9%	-	≤ 32 min for 10-km race or equivalent
		9.4			49.48 ± 2.60					
		18.5			49.05 ± 2.55 48.11 ± 2.49					
Day & Hahn 2019 [24]	Epic React Flyknit + 3 mm Nylon 11 plate + 2x 3 mm Nylon plate	5.9	10 men	3.89, 4.72	(W/kg)	(W/kg)		At 3.89 m/s: stiffest vs. control: -2.36% At 4.72 m/s: stiffest vs. control: -2.97% stiffest vs. stiff: -2.91%	-	≤ 16 min for 5-km race or equivalent ≥ 50 km/week
		10.5			14.42 ± 1.06	18.21 ± 1.14				
		17.0			14.61 ± 1.08 14.76 ± 1.07	18.22 ± 1.15 18.75 ± 1.21				
McLeod et al 2020 [22]	Saucony Freedom, CF plates with increasing stiffness	3.3 - 4.0	21 men	2.98, 4.47	(mL/kg/min) U-shaped	(mL/kg/min) U-shaped		Optimal stiffness vs. control: at 2.98 m/s: 1.93 ± 1.82% at 4.47 m/s: 3.02 ± 2.62%	-	≤ 36 min for 10-km race or equivalent
		4.5 - 5.7								
		5.2 - 6.2								
		5.8 - 7.2								
		6.5 - 10.2 8.8 - 10.5								
Beck et al 2020 [23]	Adidas Adizero Adios Boost 2 + 0.8 mm CF plate + 1.6 mm CF plate + 3.2 mm CF plate	5.2	15 men	3.5	(W/kg)	overall similar [reported in graph only]		no significant differences	tibialis anterior ≈ soleus ≈ medial gastrocnemius ≈ vastus medialis ≈ rectus femoris ≈ biceps femoris ≈ gluteus maximus ≈	≤ 25 min for 5-km race or equivalent
		12.4								
		17.2								
		33.6								

AB: Adidas Boost; CF: carbon fiber; EMG: electromyography; EVA: ethylene-vinyl acetate; k<sub>cr</sub>: critical stiffness condition; NR: non-responders; NS: Nike Streak; NVF: Nike Vaporfly; NZM: Nike Zoom Matumbo;  
PT: prototype; PU: polyurethane; R: responders; RE: running economy; VAT: ventilatory anaerobic threshold  
Italic values are inferred from other publications with same footwear

**Table S3** Stride frequency and contact time for different longitudinal bending stiffness footwear interventions.

Study	Shoe Condition	Bending Stiffness (Nm/rad)	Velocity (m/s)	Stride Frequency (Hz)			Contact Time (seconds)		
Willwacher et al 2014 [29]	Nike Free 3.0	0.3	3.5 ± 5%	-			0.239 ± 0.016 <sup>**</sup>		
	+ 0.9 mm CF plate	2.8					0.248 ± 0.017 <sup>*</sup>		
	+ 3.2 mm CF plate	6.5					0.249 ± 0.015 <sup>°</sup>		
Oh & Park 2017 [20]	Reebok ZQUICK	1.5	2.43 ± 0.23 (based on VO2max)	-			increased as bending stiffness increased [graph only]		
	+ 0.8 mm CF plate	10.0							
	+ 1.2 mm CF plate	24.5							
	+ 1.5 mm CF plate	32.1							
	+ 1.8 mm CF plate	42.1							
	+ 2.0 mm CF plate (n =1)	56.6							
Flores et al 2019 [19]	Kalenji prototype PU	6.2	3.0 ± 0.31 (90% of VAT)				0.2756 ± 0.0186		
	Kalenji prototype EVA	7.7					0.2719 ± 0.0177		
	Kalenji prototype PU + 0.9 mm CF plate	15.2					0.2787 ± 0.0188		
	Kalenji prototype EVA + 0.9 mm CF plate	17.3					0.2770 ± 0.0187		
Hoogkamer et al 2018 [5]	Adidas Adizero Adios Boost 2	7.0	3.89, 4.44, 5.00				0.212 ± 0.008 <sup>a:*</sup>		
	Nike Zoom Streak 6	9.4					0.212 ± 0.008 <sup>a:°</sup>		
	Nike Vaporfly prototype (curved CF plate)	18.5					0.213 ± 0.008 <sup>a:*,°</sup>		
Hoogkamer et al 2019 [10]	Adidas Adizero Adios Boost 2	7.0					0.191 ± 0.006		
	Nike Zoom Streak 6	9.4					0.190 ± 0.005		
	Nike Vaporfly prototype (curved CF plate)	18.5					0.192 ± 0.006		
Barnes & Kilding 2019 [8]	Men:	<7.0	3.89, 4.44, 5.00				1.458 ± 0.083		
							1.513 ± 0.080 <sup>*</sup>		
							1.570 ± 0.080 <sup>*</sup>		
	Women:	18.5	3.89, 4.17, 4.44				0.221 ± 0.017 <sup>*</sup>		
							0.205 ± 0.016		
							0.194 ± 0.016		
	Nike Zoom Matumbo 3	7.0					1.458 ± 0.088		
							1.497 ± 0.085		
							1.550 ± 0.068		
Barnes & Kilding 2019 [8]	Adidas Adizero Adios Boost 3	18.5					1.462 ± 0.078		
							1.497 ± 0.078 <sup>*</sup>		
							1.550 ± 0.063 <sup>*</sup>		
	Nike Vaporfly (curved CF plate)	18.5					1.458 ± 0.082		
							1.492 ± 0.080		
							1.550 ± 0.067		
	Nike Vaporfly+ (mass matched to Adidas)	18.5					0.227 ± 0.017 <sup>*</sup>		
							0.209 ± 0.017		
							0.209 ± 0.018		
Hunter et al 2019 [9]	Adidas Adizero Adios Boost 3	7.0	4.44	-			0.230 ± 0.040		
	Nike Zoom Streak 6	9.4					0.220 ± 0.036		
	Nike Vaporfly (curved CF plate)	18.5					0.222 ± 0.035 <sup>*</sup>		
Day & Hahn 2019 [24]	Epic React Flyknit	5.9	3.89, 4.72, 5.56				0.234 ± 0.040 <sup>*</sup>		
	+ 3 mm Nylon 11 plate	10.5					0.221 ± 0.040 <sup>*</sup>		
	+ 2x 3 mm Nylon plate	17.0					0.211 ± 0.039 <sup>*</sup>		
Cigoja et al 2019 [30]	Nike Free 5.0	1.9	3.5	-			1.472 ± 0.160 <sup>°</sup>		
	+ CF plate	19.0					1.457 ± 0.153		
							1.473 ± 0.153		
Beck et al 2020 [23]	Adidas Adizero Adios Boost 2	5.2	3.5	step time, no effect [values not reported]			1.498 ± 0.162		
	+ 0.8 mm CF plate	12.4					0.231 ± 0.042		
	+ 1.6 mm CF plate	17.2					0.220 ± 0.042		
Beck et al 2020 [23]	+ 3.2 mm CF plate	33.6					0.211 ± 0.038		

CF: carbon fiber; EVA: ethylene-vinyl acetate; PT: prototype; PU: polyurethane; RCP: respiratory compensation point; VAT: ventilatory anaerobic threshold

Italic values are inferred from other publications with same footwear

Matching symbols between conditions (<sup>\*</sup> / <sup>°</sup>) indicate values that are significantly different, <sup>a</sup> indicates main effect for condition (across all speeds)

**Table S4** Metatarsal-phalangeal joint mechanics for different longitudinal bending stiffness footwear interventions.

Study	Shoe Condition	Bending stiffness (Nm/rad)	Velocity (m/s)	MTP						
				Angle (deg)	Angular velocity (deg/sec)	Moment (Nm)	Negative work (J/kg)	Positive work (J/kg)	Power (W/kg)	Moment arm (mm)
Roy & Stefanyshyn 2006 [18]	Adidas Adistar Comp	7.2	3.7 (based on VO2max)	-	-	similar [graph only]	similar [graph only]	similar [graph only]	-	-
	+ CF plate	15.2								
	+ thicker CF plate	18.0								
Willwacher et al 2013 [31]	Nike Free 3.0	0.3	3.5 ± 5%	-29.5 ± 4.7 *	730.7 ± 113.6 *	-0.20 ± 0.08 *	-0.060 ± 0.029 *	0.017 ± 0.008 *	0.83 ± 0.36 *	-
	+ 0.9 mm CF plate	2.8								
	+ 3.2 mm CF plate	6.5								
Willwacher et al 2014 [29]	Nike Free 3.0	0.3	3.5 ± 5%	-	-	-	-	-	-	17.1 ± 8.4 *
	+ 0.9 mm CF plate	2.8								
	+ 3.2 mm CF plate	6.5								
Madden et al 2016 [27]	Adidas PT	3.2	3.2 ± 0.5 (based on VO2max)	-29.5 *	-	-	-	-	-	-
	Adidas PT + CF stiffening plates	9.2								
Oh & Park 2017 [20]	Reebok ZQUICK	1.5	2.43 ± 0.23 (based on VO2max)	Decreased with increased stiffness [graph only]	-	-	-	-	-	-
	+ 0.8 mm CF plate	10.0								
	+ 1.2 mm CF plate	24.5								
	+ 1.5 mm CF plate	32.1								
	+ 1.8 mm CF plate	42.1								
Hoogkamer et al 2019 [8]										
	+ 2.0 mm CF plate (n =1)	56.6								
Hoogkamer et al 2019 [8]	Adidas Adizero Adios Boost 2	7.0	4.44	22.9 ± 3.8 *	-	47.0 ± 7.6 *	(J/kg/step) -0.20 ± 0.05 *	(J/kg/step) 0.00 ± 0.00	[graph only]	-
	Nike Zoom Streak 6	9.4								
	Nike Vaporfly PT (curved CF plate)	18.5								
Cigoja et al 2019 [30]			3.5	-	(at peak positive power) -8.53 ± 1.43 -7.99 ± 1.28	(at peak positive power) -7.14 ± 1.67 * -14.30 ± 3.38 *	-0.19 ± 0.05 * -0.15 ± 0.05 *	0.008 ± 0.003 * 0.03 ± 0.01 *	-	similar
	Nike Free 5.0	1.9								
	+ CF plate	19.0								
Flores et al 2019 [34]			3.28 ± 0.28 (based on VAT) 4.01 ± 0.27 (based on VAT and RCP)	BL > TL [graph only]	-	BL > TL [graph only]	-0.10 ± 0.03 -0.10 ± 0.03 -0.09 ± 0.03 -0.08 ± 0.03	0.020 ± 0.006 0.017 ± 0.006 0.024 ± 0.006 0.023 ± 0.007	-	-
	Kalenji PT + top loaded CF plate	14.9								
	Kalenji PT + bottom loaded CF plate	16.0								
Beck et al 2020 [23]	Adidas Adizero Adios Boost 2	5.2	3.5	similar [graph only]	-	similar [graph only]	-	-	-	-
	+ 0.8 mm CF plate	12.4								
	+ 1.6 mm CF plate	17.2								
	+ 3.2 mm CF plate	33.6								
Cigoja et al 2020 [48]			90% LT	-	-	-	-	(% total) 1.18 ± 0.52 4.47 ± 1.39	-	-
	Nike Free 2018	2.7								
	+ CF plate	21.5								

BL: bottom loaded; CF: carbon fiber; EVA: ethylene-vinyl acetate; PT: prototype; PU: polyurethane; RCP: respiratory compensation point; TL: top loaded; VAT: ventilatory anaerobic threshold  
LT: lactate threshold; Matching symbols between conditions (\* / °) indicate values that are significantly different



**Table S5** Ankle joint mechanics for different longitudinal bending stiffness footwear interventions.

Study	Shoe Condition	Bending stiffness (Nm/rad)	Velocity (m/s)	Ankle						
				Angle (deg)	Angular velocity (deg/sec)	Moment (Nm)	Negative work (J/kg)	Positive work (J/kg)	Power (W)	Moment arm (mm)
Roy & Stefanyshyn 2006 [18]	Adidas Adistar Comp + CF plate + thicker CF plate	7.2 15.2 18.0	3.7 (based on VO2max)	-	-	231.3 ± 24.7 * 235.9 ± 24.7 * 240.6 ± 26.5 *	(J) -64.4 ± 13.0* [graph only] -71.2 ± 13.8*	similar [graph only]	-	-
Willwacher et al 2014 [29]	Nike Free 3.0 + 0.9 mm CF plate + 3.2 mm CF plate	0.3 2.8 6.5	3.5 ± 5%	-	-	(Nm/kg) -1.58 ± 0.24 * -1.52 ± 0.29 ** -1.61 ± 0.18 °	-	-	-	136.1± 10.6 * 148.2 ± 8.9 * 157.4 ± 6.5 *
Madden et al 2016 [27]	Adidas PT Adidas PT + CF stiffening plates	3.2 9.2	3.2 ± 0.5 (based on VO2max)	14.4 13.5	290 * 275 *	-	-	-	-	-
Oh & Park 2017 [20]	Reebok ZQUICK + 0.8 mm CF plate + 1.2 mm CF plate + 1.5 mm CF plate + 1.8 mm CF plate + 2.0 mm CF plate (n =1)	1.5 10.0 24.5 32.1 42.1 56.6	2.43 ± 0.23 (based on VO2max)	-	-	-	-	-	-	Increased with increased stiffness [graph only]
Hoogkamer et al 2019 [8]	Adidas Adizero Adios Boost 2 Nike Zoom Streak 6 Nike Vaporfly PT (curved CF plate)	7.0 9.4 18.5	4.44	21.2 ± 5.3 * 19.3 ± 4.0 ° 17.5 ± 3.9 **	similar [graph only]	264.6 ± 27.7 * 260.6 ± 23.2 254.5 ± 28.1 *	(J/kg/step) -0.87 ± 0.09 * -0.80 ± 0.10 * -0.72 ± 0.07 *	(J/kg/step) 0.92 ± 0.14 * 0.93 ± 0.19 ° 0.83 ± 0.16 **	[graph only]	similar [graph only]
Cigoja et al 2019 [30]	Nike Free 5.0 + CF plate	1.9 19.0	3.5	-	-	-	-0.46 ± 0.11 -0.46 ± 0.09	0.77 ± 0.14 0.74 ± 0.11	-	-
Flores et al 2019 [34]	Kalenji PT + top loaded CF plate Kalenji PT + bottom loaded CF plate	14.9 16.0	3.28 ± 0.28 (based on VAT)  4.01 ± 0.27 (based on VAT and RCP)	BL > TL [graph only]	-	BL > TL [graph only]	-0.485 ± 0.181 -0.481 ± 0.184 -0.535 ± 0.163 -0.541 ± 0.163	0.736 ± 0.134 0.725 ± 0.137 0.772 ± 0.138 0.775 ± 0.136	-	-
Beck et al 2020 [23]	Adidas Adizero Adios Boost 2 + 0.8 mm CF plate + 1.6 mm CF plate + 3.2 mm CF plate	5.2 12.4 17.2 33.6	3.5	similar [graph only]	-	similar [graph only]	-	-	-	-
Cigoja et al 2020 [48]	Nike Free 2018 + CF plate	2.7 21.5	90% LT	-	-	-	-	(% total) 47.83 ± 8.31 47.78 ± 9.39	-	-

BL: bottom loaded; CF: carbon fiber; EVA: ethylene-vinyl acetate; PT: prototype; PU: polyurethane; RCP: respiratory compensation point; TL: top loaded; VAT: ventilatory anaerobic threshold  
LT: lactate threshold; Matching symbols between conditions (\* / °) indicate values that are significantly different

**Table S6** Knee joint mechanics for different longitudinal bending stiffness footwear interventions.

Study	Shoe Conditions	Bending stiffness (Nm/rad)	Velocity (m/s)	Knee							
				Angle (deg)	Angular velocity (deg/sec)	Moment (Nm)	Negative work (J/kg)	Positive work (J/kg)	Moment arm (mm)		
Roy & Stefanyshyn 2006 [18]	Adidas Adistar Comp + CF plate + thicker CF plate	7.2 15.2 18.0	3.7 (based on VO2max)	-	-	similar [graph only]	similar [graph only]	similar [graph only]	-		
Willwacher et al 2014 [29]	Nike Free 3.0	0.3	3.5 ± 5%	-	-	-	-	-	11.4 ± 24.0 **		
	+ 0.9 mm CF plate	2.8							29.4 ± 21.8 *		
	+ 3.2 mm CF plate	6.5							34.7 ± 18.0 °		
Madden et al 2016 [19]	Adidas PT	3.2	3.2 ± 0.5	36.1	251	-	-	-	-		
	Adidas PT + CF stiffening plates	9.2	(based on VO2max)	35.1	257						
Hoogkamer et al 2019 [10]	Adidas Adizero Adios Boost 2	7.0	4.44	43.2 ± 4.0	similar [graph only]	176.0 ± 26.4	-0.53 ± 0.15	0.23 ± 0.09	-		
	Nike Zoom Streak 6	9.4		43.4 ± 4.3		174.0 ± 22.8	-0.56 ± 0.15	0.24 ± 0.09			
	Nike Vaporfly PT (curved CF plate)	18.5		43.1 ± 4.4		175.5 ± 25.5	-0.53 ± 0.15	0.22 ± 0.08			
Cigoja et al 2019 [30]	Nike Free 5.0	1.9	3.5	-	-	-	-0.60 ± 0.17	0.22 ± 0.01 *	-		
	+ CF plate	19.0					-0.61 ± 0.15	0.20 ± 0.05 *			
Flores et al 2019 [34]	Kalenji PT + top loaded CF plate	14.9	3.28 ± 0.28 (based on VAT)	-	-	-	-0.500 ± 0.132	0.377 ± 0.099 <sup>a:*</sup>	-		
		16.0					-0.495 ± 0.130	0.380 ± 0.099 <sup>a:*</sup>			
	Kalenji PT + bottom loaded CF plate						-0.496 ± 0.153	0.383 ± 0.097 <sup>a:*</sup>			
							-0.522 ± 0.151	0.414 ± 0.104 <sup>a:*</sup>			
Beck et al 2020 [23]	Adidas Adizero Adios Boost 2	5.2	3.5	similar [graph only]	-	similar [graph only]	-	-	-		
	+ 0.8 mm CF plate	12.4									
	+ 1.6 mm CF plate	17.2									
	+ 3.2 mm CF plate	33.6									
Cigoja et al 2020 [48]	Nike Free 2018 + CF plate	2.7 21.5	90% LT	-	-	-	-	(% total) 29.06 ± 11.21 27.08 ± 11.24	-		

BL: bottom loaded; CF: carbon fiber; EVA: ethylene-vinyl acetate; PT: prototype; PU: polyurethane; RCP: respiratory compensation point; TL: top loaded; VAT: ventilatory anaerobic threshold  
LT: lactate threshold; Matching symbols between conditions (\* / °) indicate values that are significantly different, <sup>a</sup> indicates main effect for condition (across all speeds)

**Table S7** Hip joint mechanics for different longitudinal bending stiffness footwear interventions.

Study	Shoe Conditions	Bending stiffness (Nm/rad)	Velocity (m/s)	Hip							
				Angle (deg)	Angular velocity (deg/sec)	Moment (Nm)	Negative work (J/kg)	Positive work (J/kg)	Moment arm (mm)		
Roy & Stefanyshyn 2006 [18]	Adidas Adistar Comp	7.2	3.7 (based on VO2max)	-	-	similar [graph only]	similar [graph only]	similar [graph only]	-		
	+ CF plate	15.2									
	+ thicker CF plate	18.0									
Willwacher et al 2014 [29]	Nike Free 3.0	0.3	3.5 ± 5%	-	-	-	-	-	80.3 ± 31.3 **		
	+ 0.9 mm CF plate	2.8							94.3 ± 27.3 *		
	+ 3.2 mm CF plate	6.5							100.5 ± 19.7 °		
Hoogkamer et al 2019 [10]	Adidas Adizero Adios Boost 2	7.0	4.44	similar [graph only]	similar [graph only]	similar [graph only]	-0.12 ± 0.15	0.19 ± 0.16	-		
	Nike Zoom Streak 6	9.4					-0.12 ± 0.14	0.18 ± 0.15			
	Nike Vaporfly PT (curved CF plate)	18.5					-0.10 ± 0.11	0.18 ± 0.15			
Cigoja et al 2019 [30]	Nike Free 5.0	1.9	3.5	-	-	-	-0.09 ± 0.07	0.23 ± 0.01	-		
	+ CF plate	19.0					-0.10 ± 0.06	0.24 ± 0.10			
Flores et al 2019 [34]	Kalenji PT + top loaded CF plate	14.9	3.28 ± 0.28 (based on VAT)	-	-	-	-0.173 ± 0.097	0.111 ± 0.057	-		
		16.0					-0.179 ± 0.102	0.113 ± 0.054			
	Kalenji PT + bottom loaded CF plate						-0.220 ± 0.100	0.148 ± 0.067			
							-0.228 ± 0.106	0.155 ± 0.062			
Beck et al 2020 [23]	Adidas Adizero Adios Boost 2	5.2	3.5	similar [graph only]	-	similar [graph only]	-	-	-		
	+ 0.8 mm CF plate	12.4									
	+ 1.6 mm CF plate	17.2									
	+ 3.2 mm CF plate	33.6									
Cigoja et al 2020 [48]	Nike Free 2018	2.7	90% LT	-	-	-	-	(% total)	-		
	+ CF plate	21.5						21.30 ± 10.81 19.95 ± 8.40			

BL: bottom loaded; CF: carbon fiber; EVA: ethylene-vinyl acetate; PT: prototype; PU: polyurethane; RCP: respiratory compensation point; TL: top loaded; VAT: ventilatory anaerobic threshold  
LT: lactate threshold; Matching symbols between conditions (\* / °) indicate values that are significantly different, <sup>a</sup> indicates main effect for condition (across all speeds)