Supplemental digital content

Running into fatigue: The effects of footwear on kinematics, kinetics, and energetics

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Supplemental Table 1, 'Minimalist Shoe Index' test: Footwear characteristics of both shoes based on the 'Minimalist Shoe Index' of Esculier et al. (20).

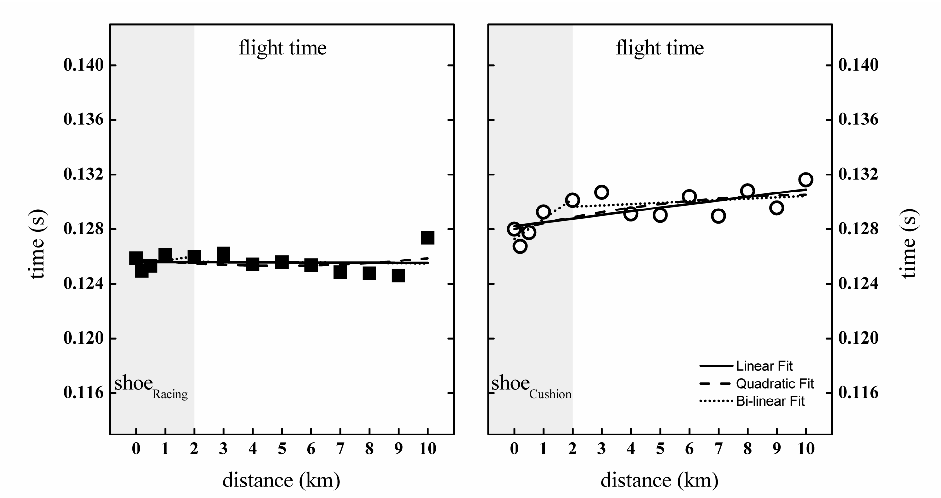
	Minimalist Shoe Index			
	$shoe_{Racing}$		$shoe_{Cushion}$	
	value	score	value	score
Shoe mass (kg)	0.170	4	0.348	0
Heel-Stack height (mm)	20	2	35	0
Forefoot height (mm)	15		28	
Heel to toe drop (mm)	5	3	7	2
Motion control and stability technologies		3		1
Longitudinal flexibility		1.5		1
Torsional flexibility		1.5		0.5
Minimalist Shoe Index		**60**		**18**

Note: The 'Minimalist Shoe Index' is a scale ranging from 1 (no minimalism at all) to 100 (perfectly minimal footwear) and indicates minimalism of the footwear type.

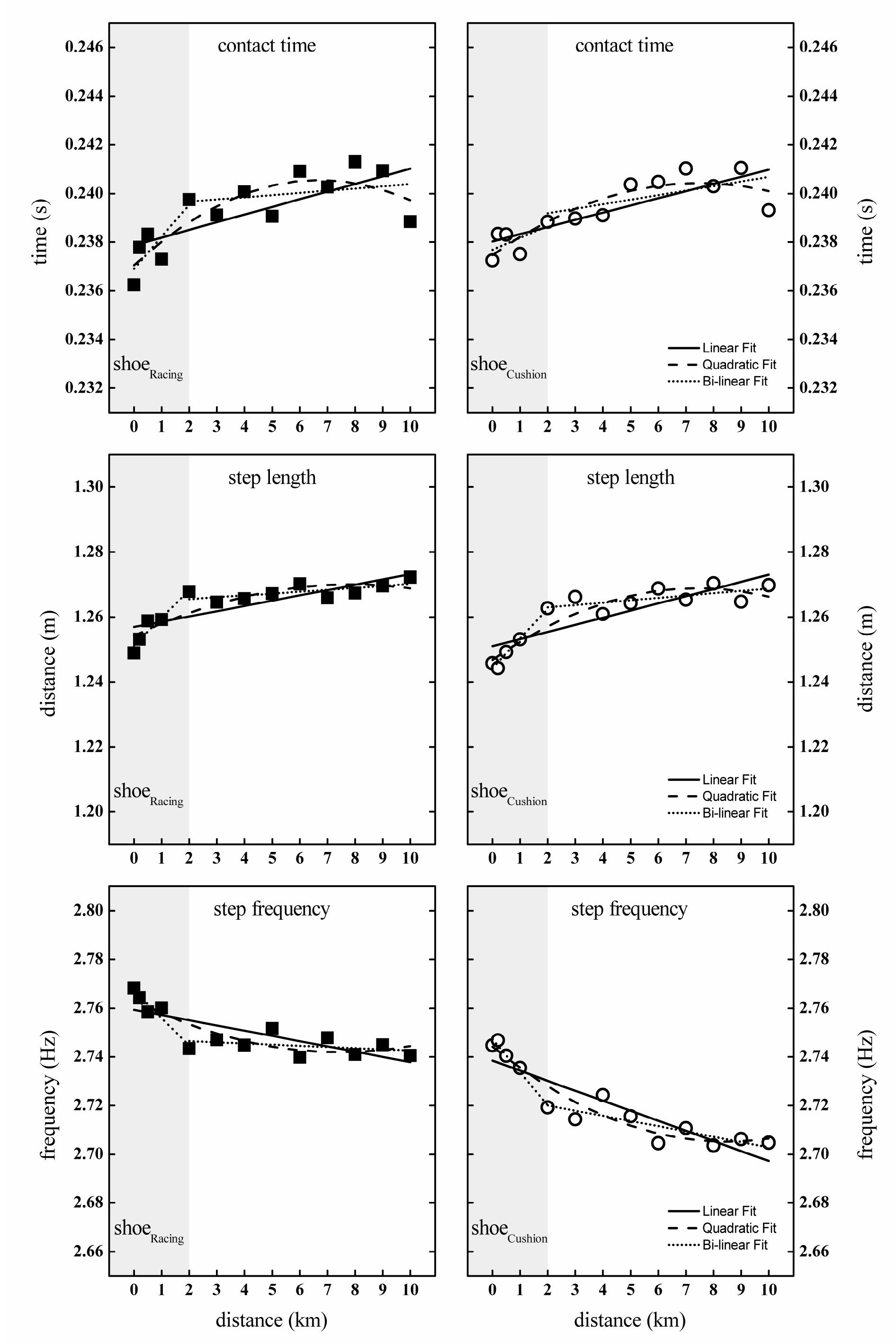
Supplemental Table 2, Spatiotemporal parameters: Spatiotemporal parameters (mean ± standard deviation) at three different distances of the 10-km treadmill run with near-maximal effort using 'Adizero Pro 4' ($Shoe_{Racing}$) and 'Glycerin 10' ($Shoe_{Cushion}$) shoes. Significant differences of pairwise comparisons between both shoes are presented by *P < 0.05 and **P < 0.01.

		Spatiotemporal parameters		
		0 km	2 km	10 km
contact time (s)	$shoe_{Racing}$	0.236 ± 0.031	0.240 ± 0.031	0.239 ± 0.032
	$shoe_{Cushion}$	0.237 ± 0.031	0.239 ± 0.030	0.239 ± 0.029
step length (m)	$shoe_{Racing}$	1.251 ± 0.209	1.270 ± 0.211	1.275 ± 0.216
	$shoe_{Cushion}$	1.250 ± 0.205	1.267 ± 0.210	1.274 ± 0.221
step frequency (Hz)	$shoe_{Racing}$	**2.768 ± 0.135** *	**2.743 ± 0.156** *	**2.740 ± 0.163** **
	$shoe_{Cushion}$	**2.745 ± 0.136**	**2.719 ± 0.156**	**2.705 ± 0.156**
flight time (s)	$shoe_{Racing}$	0.126 ± 0.024	**0.126 ± 0.024** *	0.127 ± 0.028 (P = 0.077)
	$shoe_{Cushion}$	0.128 ± 0.022	**0.130 ± 0.023**	0.132 ± 0.026

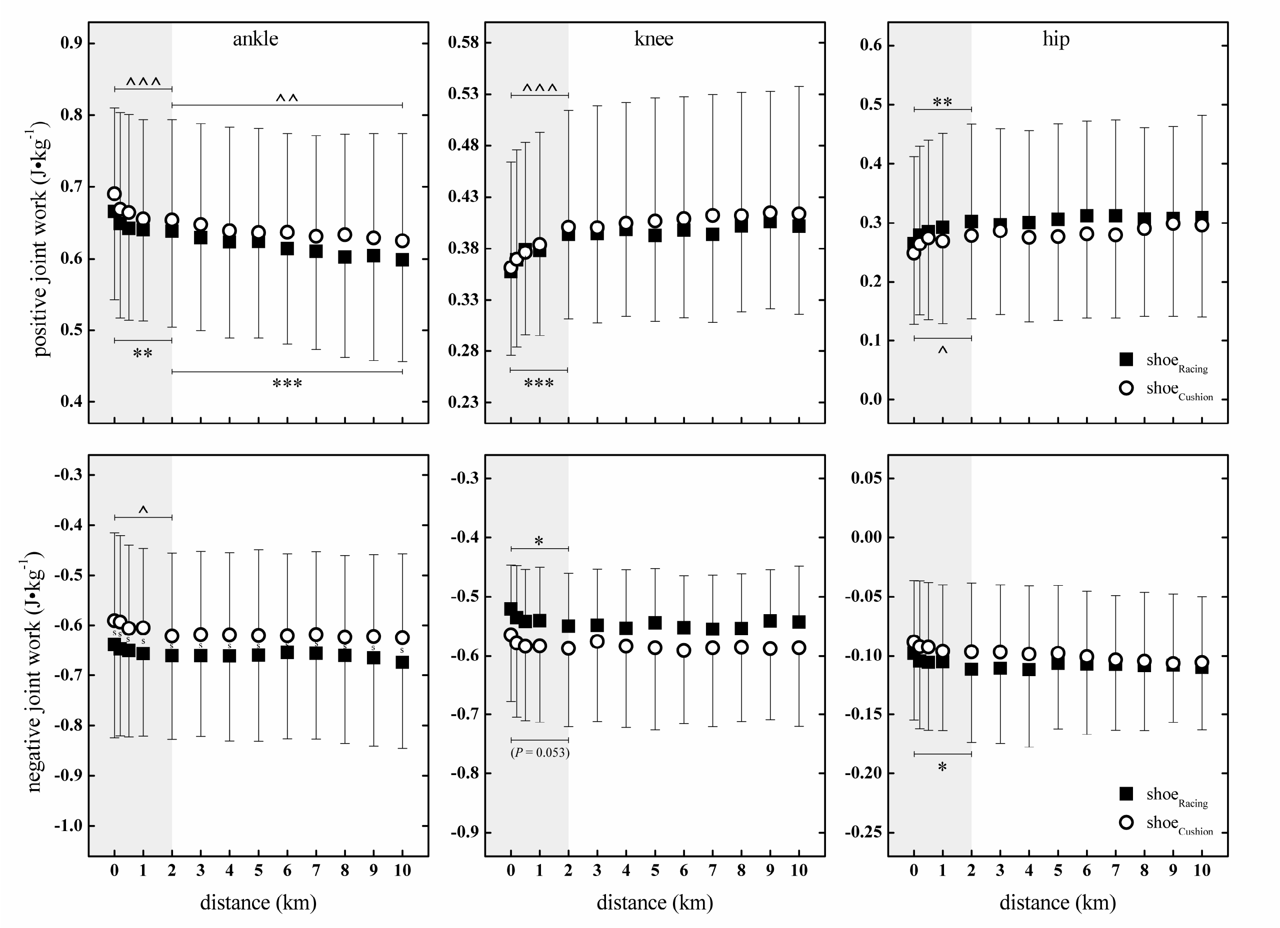
Note: The significant (P < 0.05) shoe differences of step frequency and flight time from 3 km to 9 km are presented in the Supplemental Table 5, Pairwise comparisons between shoes.



Supplemental Fig. 1, Fitting methods: Flight time as mean of both shoe conditions (■ $shoe_{Racing}$: racing flat shoe; ○ $shoe_{Cushion}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. To quantify a potential habituation and fatigue phase three different fitting methods (Solid line: Linear Fit; dashed line: Quadratic Fit; dotted line: Bi-linear Fit of 0 km to 2 km (grey area), and 2 km to 10 km) were used.



Supplemental Fig. 2, Fitting methods: Contact time, step length, and step frequency as mean of both shoe conditions (■ $\text{shoe}_{\text{Racing}}$: racing flat shoe; ○ $\text{shoe}_{\text{Cushion}}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. To quantify a potential habituation and fatigue phase three different fitting methods (Solid line: Linear Fit; dashed line: Quadratic Fit; dotted line: Bi-linear Fit of 0 km to 2 km (grey area), and 2 km to 10 km) were used.



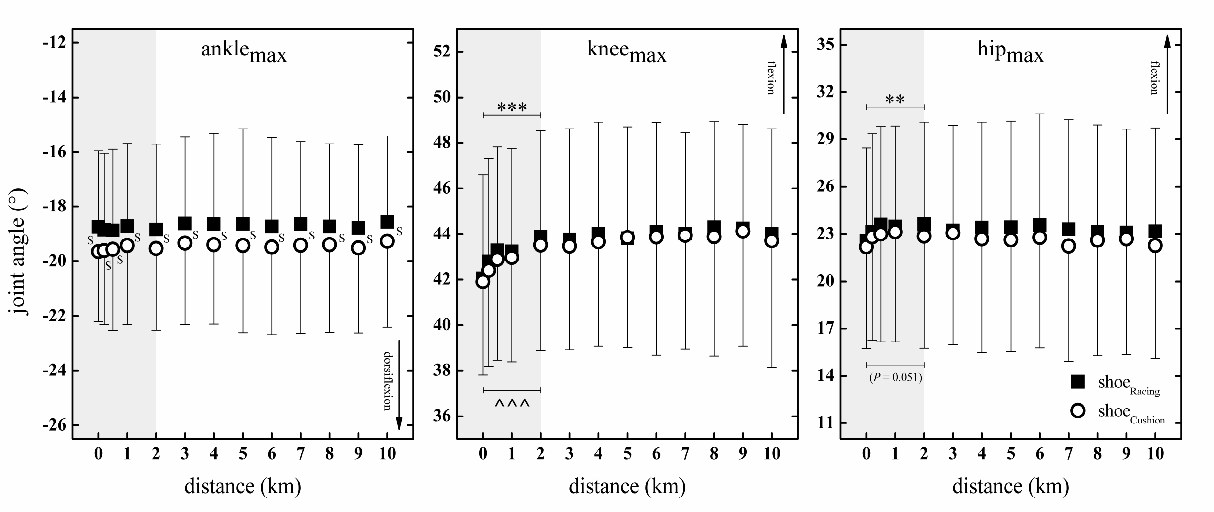
Supplemental Fig. 3 Joint work: Positive and negative work (mean ± standard deviation) at the ankle, knee, and hip joint for both shoe conditions (■ $shoe_{Racing}$: racing flat shoe; ○ $shoe_{Cushion}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. The first distance interval (0 – 2 km) was selected to assess potential habituation effects (grey area) and the second distance interval (2 – 10 km) to demonstrate fatiguing processes. Significant differences between 0 km and 2 km as well as 2 km and 10 km are represented by **P* < 0.05, ***P* < 0.01, and ****P* < 0.001 for $shoe_{Racing}$ as well as ^*P* < 0.05 and ^^^*P* < 0.001 for $shoe_{Cushion}$, respectively. Significant (*P* < 0.05) shoe differences are represented by *S*.

Supplemental Table 3, Relative joint work: Relative positive and negative work (mean ± standard deviation) at the ankle, knee, and hip joint in both shoe conditions (■ $shoe_{Racing}$: racing flat shoe; ○ $shoe_{Cushion}$: cushioned running shoe) at 0 km, 2 km, and 10 km of the 10-km treadmill run with near-maximal effort. Significant differences to 0 km are represented by **P* < 0.05, ***P* < 0.01, and ****P* < 0.001 as well as significant differences to 2 km are represented by ^*P* < 0.05, ^^*P* < 0.01, and ^^^*P* < 0.001, respectively.

		Relative joint work [%]		
		0 km	2 km	10 km
hip_{pos}	$shoe_{Racing}$	19.4 ± 8.3	21.4 ± 8.9**	22.3 ± 9.4**
	$shoe_{Cushion}$	18.5 ± 7.0	20.2 ± 7.7	21.5 ± 8.5**
$knee_{pos}$	$shoe_{Racing}$	28.3 ± 6.7	30.2 ± 7.2**	31.5 ± 7.4***,^
	$shoe_{Cushion}$	27.8 ± 6.9	30.2 ± 7.9***	30.9 ± 7.7***
$ankle_{pos}$	$shoe_{Racing}$	52.3 ± 7.5	48.3 ± 7.9***	46.2 ± 8.4***,^^^
	$shoe_{Cushion}$	53.7 ± 8.1	49.6 ± 9.4***	47.5 ± 10.2***,^^^
hip_{neg}	$shoe_{Racing}$	7.6 ± 3.5	8.3 ± 3.8	8.2 ± 3.3
	$shoe_{Cushion}$	6.9 ± 3.4	7.1 ± 3.3	7.7 ± 3.1
$knee_{neg}$	$shoe_{Racing}$	42.2 ± 6.4	42.1 ± 6.7	41.4 ± 6.8
	$shoe_{Cushion}$	46.0 ± 7.4	45.4 ± 8.2	44.9 ± 7.8
$ankle_{neg}$	$shoe_{Racing}$	50.2 ± 7.2	49.6 ± 7.2	50.4 ± 6.9
	$shoe_{Cushion}$	47.1 ± 8.3	47.5 ± 8.6	47.4 ± 8.4

Supplemental Table 4, Pairwise comparisons between shoes: Pairwise comparisons (*P*-values) between two different shoes (racing flat shoe: 'Adizero Pro 4'; cushioned running shoe: 'Glycerin 10') at 13 distances of 10-km treadmill run with near-maximal effort for spatiotemporal parameters, maximal (max) joint angles, joint angles at foot touch-down (TD) and toe-off (TO), angle between the foot and the treadmill surface at touch-down (foot-TS_{TD}), maximal external joint torques, and positive (pos) and negative (neg) joint work. All significant differences ($P < 0.05$) are represented by bold printed *P*-values.

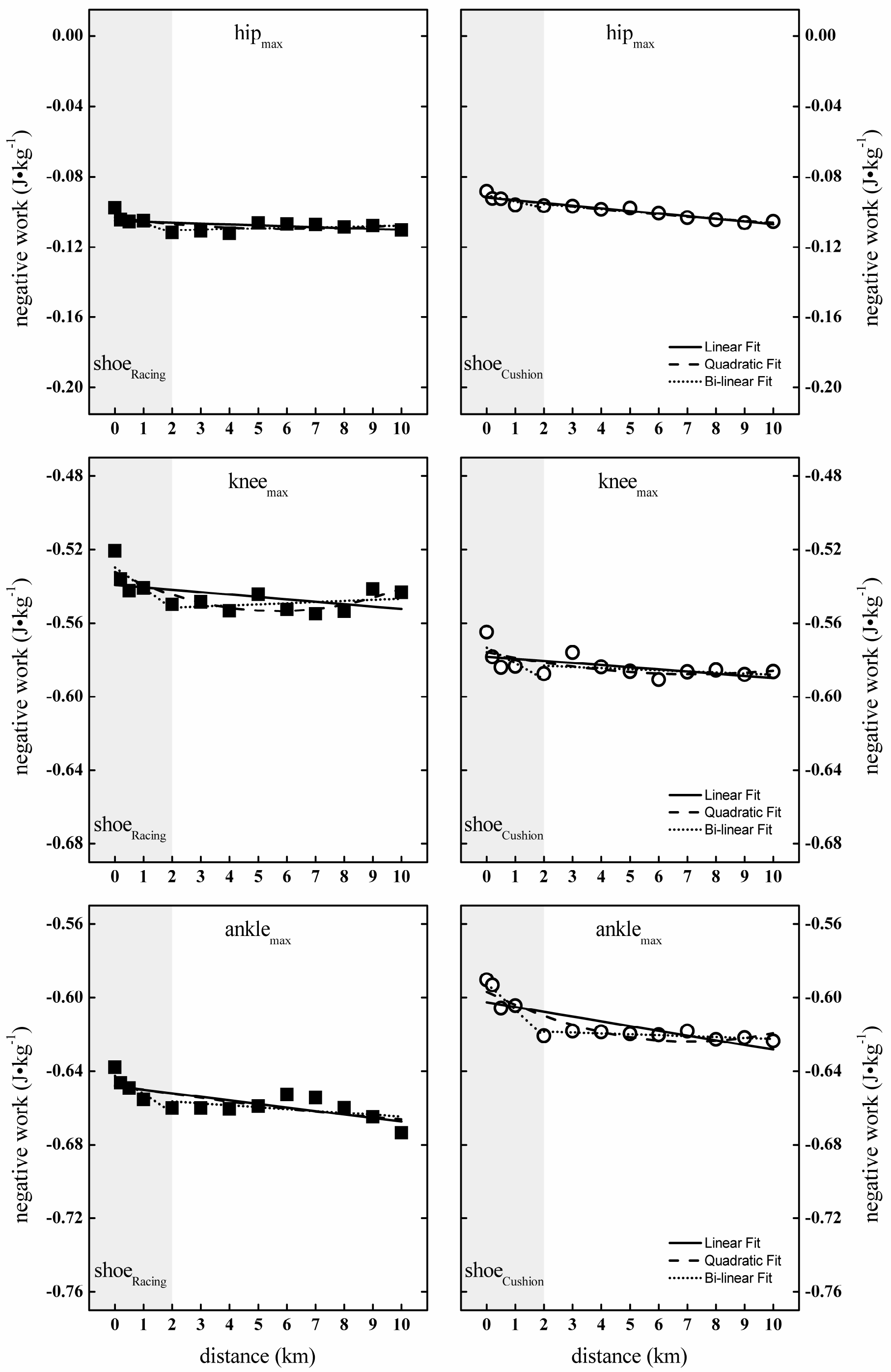
		Pairwise comparisons (shoes)												
		0 km	0.2 km	0.5 km	1 km	2 km	3 km	4 km	5 km	6 km	7 km	8 km	9 km	10 km
Spatio-temporal	contact time	0.566	0.707	0.993	0.874	0.489	0.921	0.436	0.349	0.743	0.604	0.549	0.949	0.807
	step length	0.778	0.151	0.184	0.395	0.579	0.541	0.518	0.810	0.907	0.731	0.250	0.480	0.916
	step frequency	**0.020**	0.080	0.119	**0.023**	**0.031**	**0.016**	**0.016**	**0.001**	**< 0.000**	**< 0.000**	**0.002**	**< 0.000**	**0.007**
	flight time	0.314	0.355	0.124	0.086	**0.028**	**0.032**	**0.009**	**0.032**	**0.004**	**0.018**	**0.007**	**0.015**	0.077
Angle	hip $flexion_{max}$	0.487	0.577	0.370	0.586	0.364	0.813	0.307	0.287	0.241	0.164	0.550	0.587	0.256
	knee $flexion_{max}$	0.762	0.376	0.391	0.580	0.468	0.585	0.498	0.965	0.674	0.882	0.457	0.813	0.607
	ankle $dorsiflexion_{max}$	**0.008**	**0.008**	**0.032**	**0.028**	**0.020**	**0.029**	**0.045**	**0.036**	**0.044**	**0.031**	**0.048**	**0.011**	**0.040**
	knee $flexion_{TD}$	0.155	0.094	0.074	0.063	0.236	0.583	0.556	0.114	0.058	0.068	0.180	0.072	0.166
	ankle $dorsiflexion_{TD}$	**< 0.000**	**< 0.000**	**0.001**	**0.003**	0.191	0.158	0.087	0.109	0.249	0.567	0.317	0.187	0.108
	ankle $plantarflexion_{TO}$	**0.002**	**0.002**	**0.002**	**0.001**	**< 0.000**	**< 0.000**	**0.001**	**0.002**	**0.003**	**0.004**	**0.048**	**0.016**	**0.035**
	foot-TS_{TD}	**0.010**	**0.011**	0.051	0.077	0.905	0.921	0.854	0.561	0.633	0.426	0.691	0.559	0.354
Ext. Torque	hip $flexion_{max}$	0.873	0.633	0.818	0.793	0.693	0.973	0.565	0.637	0.421	0.579	0.582	0.547	0.340
	knee $flexion_{max}$	0.144	0.266	0.211	0.140	0.176	0.263	0.129	0.112	0.137	0.145	0.165	0.107	0.136
	ankle $dorsiflexion_{max}$	0.163	**0.034**	0.071	0.056	0.139	0.141	0.161	0.101	0.536	0.320	0.506	0.233	0.255
Work	hip_{pos}	0.420	0.416	0.462	0.159	0.204	0.527	0.199	0.193	0.114	0.151	0.511	0.761	0.654
	$knee_{pos}$	0.837	0.981	0.898	0.780	0.740	0.807	0.760	0.520	0.633	0.424	0.637	0.690	0.621
	$ankle_{pos}$	0.159	0.251	0.250	0.345	0.332	0.233	0.359	0.463	0.122	0.141	0.064	0.142	0.116
	hip_{neg}	0.276	0.092	0.089	0.194	0.120	0.083	0.073	0.331	0.481	0.557	0.683	0.872	0.618
	$knee_{neg}$	0.062	0.133	0.153	0.129	0.188	0.344	0.259	0.155	0.149	0.260	0.226	0.078	0.130
	$ankle_{neg}$	**0.012**	**0.002**	**0.008**	**0.003**	**0.019**	**0.004**	**0.006**	**0.010**	**0.019**	**0.010**	**0.007**	**0.015**	**0.004**



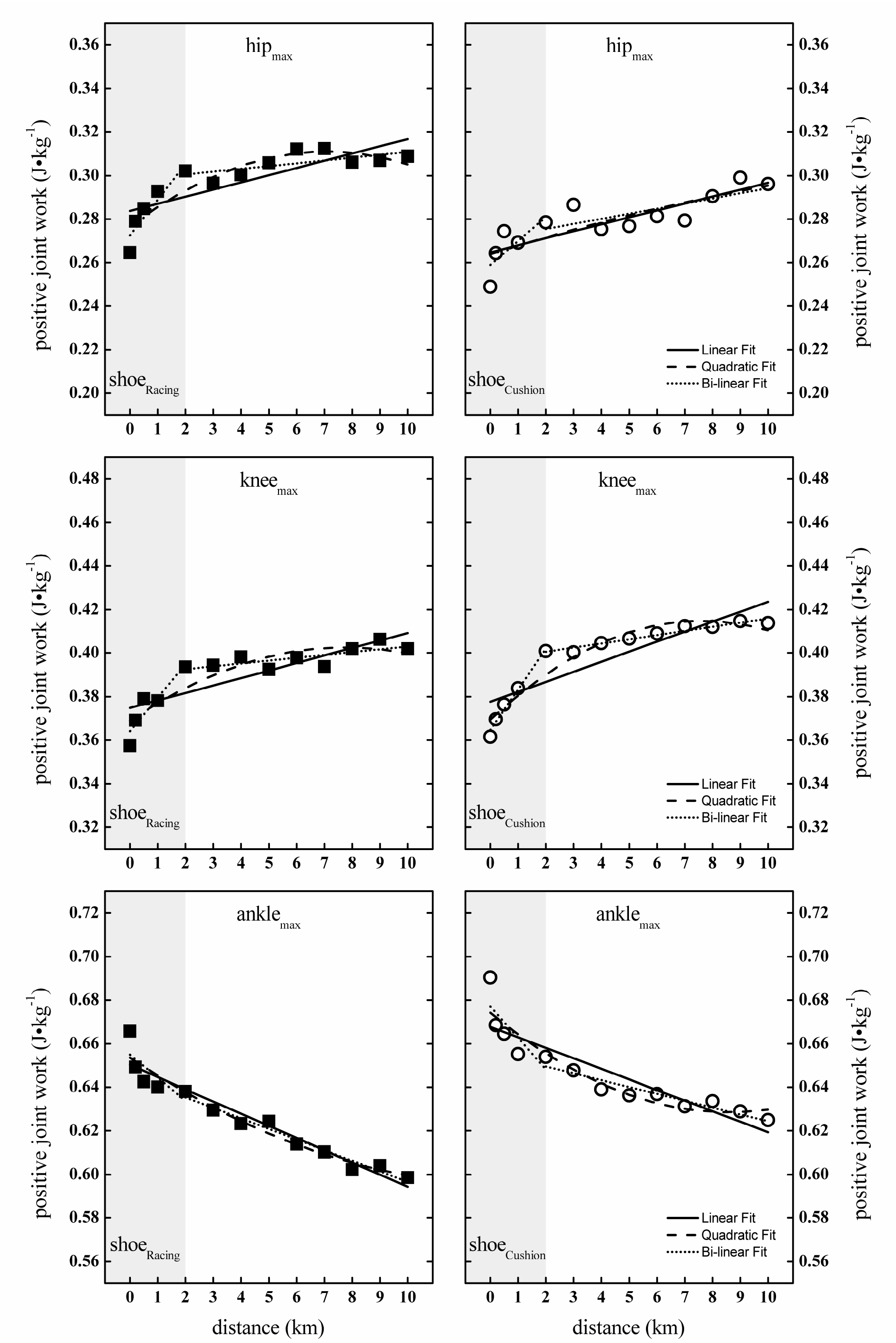
Supplemental Fig. 4, Maximal joint angle: Joint angles (mean ± standard deviation) at the ankle, knee, and hip in both shoe conditions (■ shoe$_{Racing}$: racing flat shoe; ○ shoe$_{Cushion}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. The first distance interval (0 – 2 km) was selected to assess potential habituation effects (grey area) and the second distance interval (2 – 10 km) to demonstrate fatiguing processes. Significant differences between 0 km and 2 km are represented by $^{**}P < 0.01$ and $^{***}P < 0.001$ for shoe$_{Racing}$ as well as ^^^$P < 0.001$ for shoe$_{Cushion}$, respectively. Significant ($P < 0.05$) shoe differences are represented by *S*.

Supplemental Table 5, Sum of squared errors: The sum of squared errors (SSE), is the sum of the squares of residuals (deviations predicted from actual empirical values of data). It is a measure of the discrepancy between the data and an estimation model. Three models were used: A linear model (all data: 0 – 10 km), a quadratic model (all data: 0 – 10 km), and a bi-linear model (two parts: 0 – 2 km, and 2 – 10 km). Smallest SSE indicates a tight fit of the model to the data and are presented in bold numbers.

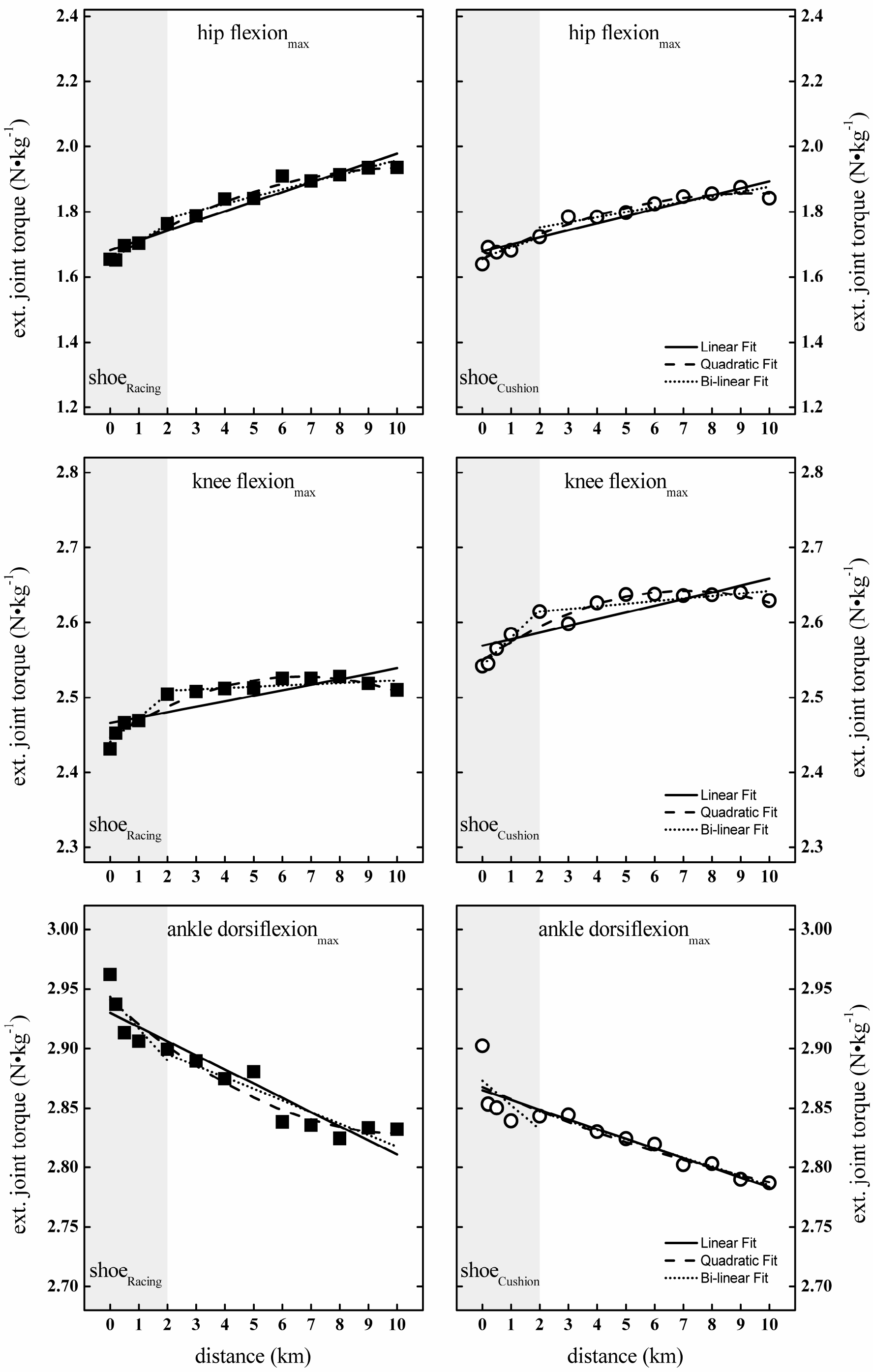
		Sum of squared errors					
		$shoe_{Racing}$			$shoe_{Cushion}$		
		linear	quadratic	bi-linear	linear	quadratic	bi-linear
Spatio-temporal	contact time	0.000013	**0.000007**	0.000008	0.000006	**0.000004**	0.000005
	step length	0.000189	0.000120	**0.000044**	0.000295	0.000128	**0.000057**
	step frequency	0.000424	0.000267	**0.000138**	0.000576	0.000271	**0.000174**
	flight time	0.000007	**0.000006**	0.000007	0.000012	0.000011	**0.000008**
Angle	hip $flexion_{max}$	0.955236	0.707457	**0.537798**	0.909557	0.816054	**0.682976**
	knee $flexion_{max}$	1.962268	0.965888	**0.544911**	1.727320	0.523274	**0.382027**
	ankle $dorsiflexion_{max}$	0.086388	**0.079241**	0.082480	0.085155	0.076608	**0.070106**
	knee $flexion_{TD}$	2.552274	1.315663	**1.023197**	3.376911	1.159855	**0.358898**
	ankle $dorsiflexion_{TD}$	1.685650	1.666236	**1.278779**	5.232915	2.869981	**0.591962**
	ankle $plantarflexion_{TO}$	0.872121	0.240680	**0.135859**	0.158402	0.149285	**0.141063**
	foot-TS_{TD}	3.292791	3.217530	**2.274766**	9.490161	4.550620	**0.869404**
Ext. Torque	hip $flexion_{max}$	0.008876	**0.001759**	0.003282	0.007528	**0.002583**	0.004109
	knee $flexion_{max}$	0.004156	0.000714	**0.000643**	0.004499	0.000949	**0.000919**
	ankle $dorsiflexion_{max}$	0.002801	**0.001685**	0.001926	0.002055	0.001987	**0.001689**
Work	hip_{pos}	0.000845	0.000358	**0.000240**	0.000640	0.000634	**0.000491**
	$knee_{pos}$	0.000754	0.000434	**0.000182**	0.000885	0.000248	**0.000035**
	$ankle_{pos}$	0.000380	0.000279	**0.000275**	0.000848	0.000448	**0.000394**
	hip_{neg}	0.000136	0.000107	**0.000051**	0.000029	0.000027	**0.000019**
	$knee_{neg}$	0.000788	0.000340	**0.000328**	0.000358	0.000306	**0.000249**
	$ankle_{neg}$	0.000415	0.000411	**0.000262**	0.000581	0.000290	**0.000071**



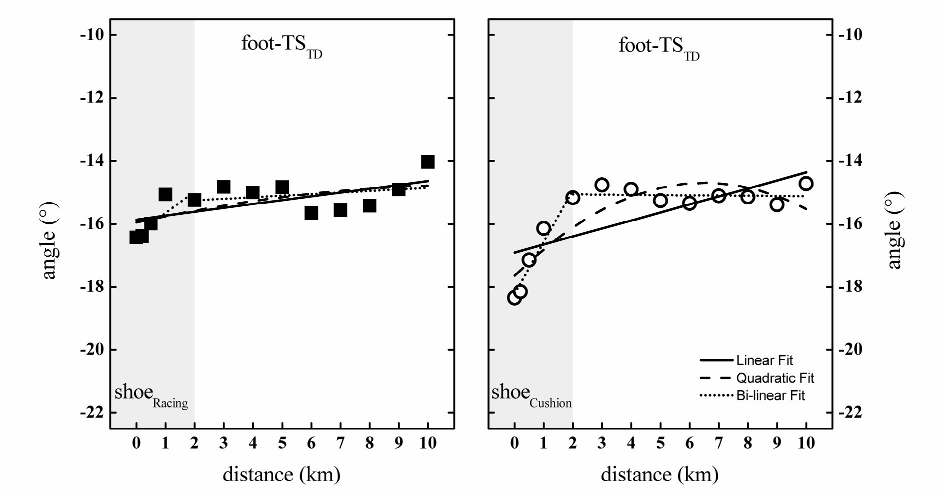
Supplemental Fig. 5, Fitting methods: Negative joint work at the hip, knee, and ankle as mean of both shoe conditions (■ $shoe_{Racing}$: racing flat shoe; ○ $shoe_{Cushion}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. To quantify a potential habituation and fatigue phase three different fitting methods (Solid line: Linear Fit; dashed line: Quadratic Fit; dotted line: Bi-linear Fit of 0 km to 2 km (grey area), and 2 km to 10 km) were used.



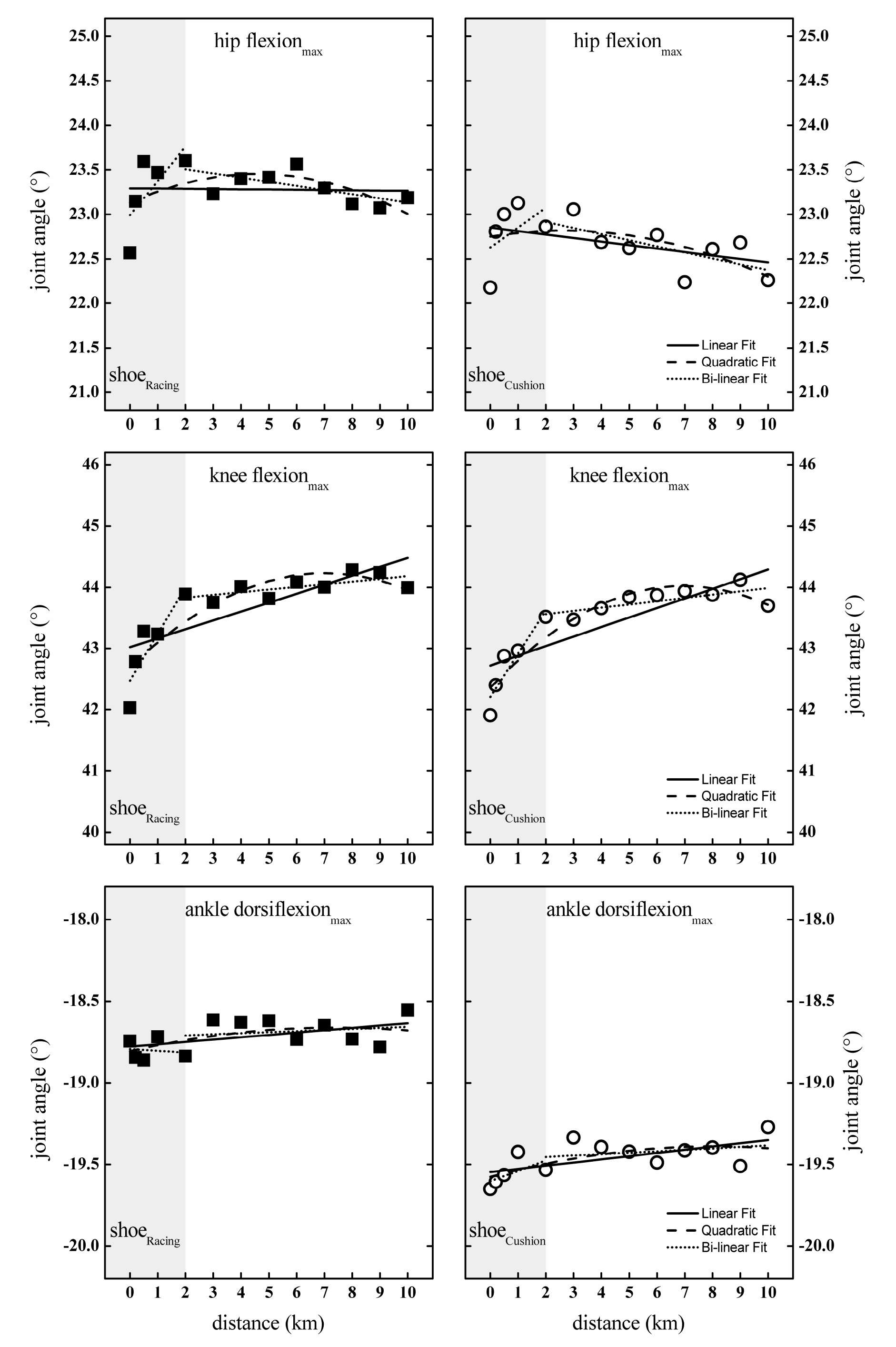
Supplemental Fig. 6, Fitting methods: Positive joint work at the hip, knee, and ankle as mean of both shoe conditions (■ shoe$_{Racing}$: racing flat shoe; ○ shoe$_{Cushion}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. To quantify a potential habituation and fatigue phase three different fitting methods (Solid line: Linear Fit; dashed line: Quadratic Fit; dotted line: Bi-linear Fit of 0 km to 2 km (grey area), and 2 km to 10 km) were used.



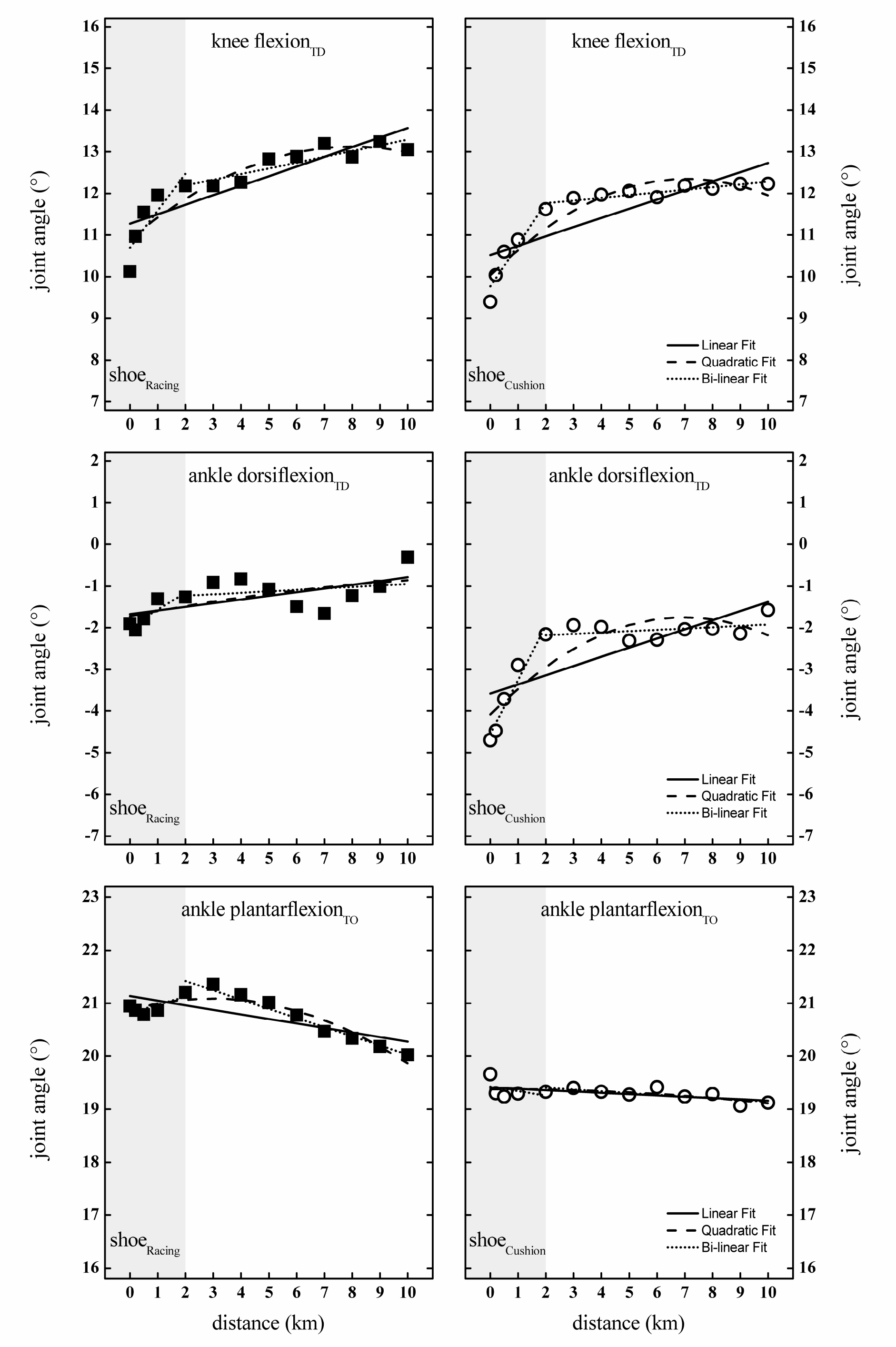
Supplemental Fig. 7, Fitting methods: Maximum external joint torque at the hip, knee, and ankle as mean of both shoe conditions (■ shoe$_{Racing}$: racing flat shoe; ○ shoe$_{Cushion}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. To quantify a potential habituation and fatigue phase three different fitting methods (Solid line: Linear Fit; dashed line: Quadratic Fit; dotted line: Bi-linear Fit of 0 km to 2 km (grey area), and 2 km to 10 km) were used.



Supplemental Fig. 8, Fitting methods: Angle between foot and treadmill surface at touch-down (foot-TS$_{TD}$) as mean of both shoe conditions (■ shoe$_{Racing}$: racing flat shoe; ○ shoe$_{Cushion}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. To quantify a potential habituation and fatigue phase three different fitting methods (Solid line: Linear Fit; dashed line: Quadratic Fit; dotted line: Bi-linear Fit of 0 km to 2 km (grey area), and 2 km to 10 km) were used.



Supplemental Fig. 9, Fitting methods: Maximum joint angle at the hip, knee, and ankle as mean of both shoe conditions (■ shoe$_{Racing}$: racing flat shoe; ○ shoe$_{Cushion}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. To quantify a potential habituation and fatigue phase three different fitting methods (Solid line: Linear Fit; dashed line: Quadratic Fit; dotted line: Bi-linear Fit of 0 km to 2 km (grey area), and 2 km to 10 km) were used.



Supplemental Fig. 10, Fitting methods: Knee and ankle joint angle at touch-down as well as ankle joint angle at toe-off as mean of both shoe conditions (■ shoe$_{Racing}$: racing flat shoe; ○ shoe$_{Cushion}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. To quantify a potential habituation and fatigue phase three different fitting methods (Solid line: Linear Fit; dashed line: Quadratic Fit; dotted line: Bi-linear Fit of 0 km to 2 km (grey area), and 2 km to 10 km) were used.