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The biomechanics of maintaining effective force application across cycling positions

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Abstract

Cyclists are known to change their cycling position to reduce aerodynamic drag. Research has shown that this compromises their physical capacity to perform, but there is considerable inter-individual variability present. Proposed training specificity effects by cycling position do not explain all of the observations in the literature, so a search for other influencing parameters is warranted and might help practitioners to further optimise cycling position. This study captured full body kinematics and 2D crank forces in 19 Time-Trial (TT) and 36 Road trained cyclists. Data in preferred and standardised cycling positions were systematically evaluated and showed that, amongst other kinematic differences, TT cyclists prefer a more forwardly positioned hip joint over Road cyclists. Despite their different setup, no effects in mechanical effectiveness were seen between the groups when tested in their preferred position. Across the standardised positions, the full cohort showed lower mechanical effectiveness when lowering trunk angle. However, significant group by position interactions showed this effect to be less extreme for the TT group. Kinematic data revealed that an increased pelvic tilt resulted in increased hip flexion and induced a more dorsiflexed ankle angle. In addition, linear hip position acutely responded to positional changes by moving forwards when the trunk angle was lowered. A more forwards hip position is thus associated with maintaining a better mechanical effectiveness in aerodynamic cycling positions. This suggests that there is potential to mitigate the effect of negative crank forces in aerodynamic positions by acutely adjusting the saddle placement to facilitate linear hip movement.

Keywords: Mechanical Effectiveness IFE; Crank Force; Bike Fitting Aerodynamics

1. Introduction

Through extensive wind-tunnel testing the scientific literature has developed a comprehensive understanding of the role of air resistance in cycling and the potential performance benefits obtained from positional changes during competitive cycling events (e.g., Blocken et al., 2018; Lukes et al., 2005; Underwood & Jermy, 2013). On the other hand, the biomechanical and physiological consequences of such aerodynamic positions (AP), which have shown negative effects on power producing capacity (Ashe et al., 2003; Fintelman et al., 2015a) and metabolic efficiency (Fintelman et al., 2015b; Gnehm et al., 1997; Peveler et al., 2005), are not fully understood. Indeed, the competitive cycling community is becoming increasingly aware of the necessity to strike an appropriate balance between aerodynamic advantages and the cyclist's physical performance (Buckley, 2018). Objectively determining this balance is complicated due to a limited understanding of how physical performance is affected by upper body position. Critically, data from several studies suggest that cyclists training for Time-Trials (TT) – either as a cycling discipline or as part of a non-drafting triathlon – appear to show smaller reductions in metabolic efficiency and power producing capabilities when acutely changing upper body position (Dorel et al., 2009; Jobson et al., 2008; Peveler et al., 2004; Peveler et al., 2005).

As performance in these events is heavily determined by both the average power and aerodynamic drag, cyclists competing in these events typically complete a large proportion of their training in AP. Taking into consideration the trained position to explain group differences in acute positional responses seems therefore a valid assumption. However, while an important role for the specificity of training position is likely, it does not appear to fully explain the observed group differences. Evidence of TT trained cyclists showing negative metabolic effects with positional changes (Evangelisti et al., 1995), and of cyclists not trained in TT (Road) showing unchanged metabolic demands when acutely

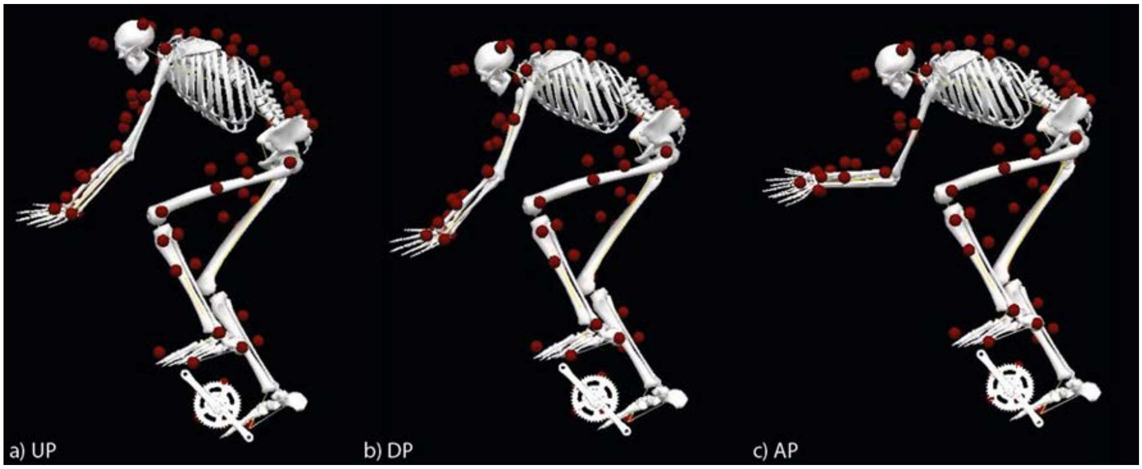

Fig. 1. Cycling positions.

changing between positions (Franke et al., 1994; Grappe et al., 1998) suggest factors other than training specificity are also impacting the acute responses to positional changes.

Reviewing positional characteristics between studies to explain such discrepancies in outcomes only allows for limited speculation on the underlying mechanisms. A contributing factor restricting comparisons across studies is the limited reporting of the biomechanical parameters, with many studies only providing a qualitative description of position (e. g. Ashe et al., 2003; Chapman et al., 2008; Charlton et al., 2017; Grappe et al., 1998; Origenes et al., 1993; Peveler et al., 2005). When a quantitative metric of trunk angle is provided, often no further detail is supplied on the subsequent effects of leg kinematics and positioning (Fintelman et al., 2014) or crank forces (Heil et al., 1997). Given the intrinsic relationship between leg positioning and effective force application (Van Ingen Schenau et al., 1992; Sanderson et al., 2003), data on both parameters combined with objective metrics defining cycling position are required to systematically evaluate the acute biomechanical responses to positional changes.

Clearly, if negative physical effects of positional changes could be mitigated by appropriate positioning this would have major benefits for practitioners preparing cyclists for competition. Arriving more readily at a position that better balances physical performance and aerodynamic drag can save valuable training hours in a sub-optimal position. Research that systematically evaluates the kinematic responses to positional changes, combined with corresponding crank force parameters can provide insights with potential to reduce negative physical performance effects. RoadCarrying out research across TT and Road cyclists allows any acute responses to be placed within the context of any position-specific training adaptations that may have taken place. Therefore, this study aims to generate a detailed analysis of the differences in cycling biomechanics induced by changes to upper body position and to investigate how these responses differ between TT and Road trained cyclists. This will help inform the practical application of different upper body positions in competitive cycling.

2. Methods

A total of 56 competitive male cyclists were recruited at local British cycling clubs - which in the UK are characterised by having subgroups dedicated to TT competition. These participants were allocated to the TT group if they reported that the majority of their training was performed in a TT position over the last 2 years or longer. Participants without any training history in TT positions were allocated to the Road group. Road Prior to participation, participants underwent medical screening to ensure they were free of any neurological condition or musculoskeletal injuries or pain, with additional focus on the lower body because of the potential implications on subsequent biomechanical measurements.

All participants were tested in their preferred position (PP) on a customised Wattbike Pro ergometer (Wattbike Ltd, Nottingham, UK). This Wattbike was customised to reduce its q-factor to 155 mm, to allow for an extended range of vertical, horizontal and angular adjustments of saddle and handlebar, and to allow for an option to swap between different handlebars, crank lengths and saddles. These structural modifications were executed by

its manufacturers to ensure that the integrity of the system's instrumentation and calibration were not affected. This study was approved by the University's Research Ethics committee and all participants provided informed consent.

Upon arrival, retroreflective markers were placed on landmarks of the participant's bike to establish their PP. Their relative position was determined by a brief recording of these markers on the stationary, supported bike, using a 4-camera optoelectronic setup (Oqus 7+, Qualisys, Sweden). This process created 3D coordinates of the saddle and handlebar position relative to the bottom bracket and saddle inclination. For TT bikes the position of the elbow pads and ends of aero extensions were recorded, for dropped-bar bikes the markers were placed in the 'notch' on the top of the brake/shifter hoods. To record the position and orientation of the saddle, markers were placed on the rear, centre and nose of the saddle. This workflow allowed accurate setting of the modified Wattbike to match the participant's bike's geometry. To replicate the participant's PP as closely as possible, the saddle and pedals were transferred from the participant's bike to the ergometer and a crank was fitted that matched the length used on that bike. Following a standardised 13-minute warm-up, participants underwent a 20-minute self-paced effort at a self-selected cadence with the instruction to achieve maximal average power for the duration of the test. The results of this effort, reflective of the intensity of a 10-mile TT (a distance regularly raced in the UK), determined the'race pace' power output at which subsequent measurements would take place.

In addition to PP, participants were tested in three standardised cycling positions (Fig. 1). The first two were an upright (UP) and dropped position (DP) defined to have trunk angles of 40° and 30°, respectively, with the saddle model and position as per the participant's own setup and with hands on the brake hoods. The third position was an AP where the forearms and hands were placed on a dedicated aerodynamic handlebar extension (Vola, 3 T, Bergamo, Italy) and the trunk angle was reduced to 24°. The ergometer settings to achieve these positions (UP, DP and AP) were established during the first visit by capturing markers on the left side. Dynamic data of these markers were livestreamed to a custom written Matlab script that calculated planar angles for the hip and knee, averaged over three revolutions and presented in real time to facilitate rapid real-time adjustments. This allowed for alterations to the handlebar position while maintaining saddle position and the distance from the saddle to the handlebar (the reach) to achieve UP, DP and AP conditions. Comprehensive ergometer settings in each position were recorded and reproduced during a second visit.

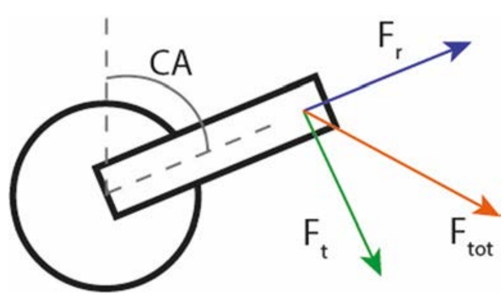

Fig. 2. Definition of crank angle (CA), tangential crank force (F_t), radial crank force (F_r) and total crank force (F_{tot}).

The average power output and cadence achieved during the 20-minute test were set as target values when participants underwent biomechanical measurements during a second testing day, separated by an interval of at least 48 h from the maximal test. Following the standardised 13-minute warm-up, participants were asked to cycle in each of the four testing positions for 3 min where a 60-second data capture took place in the final minute. Testing order was randomised.

Tangential (Ft) and radial (Fr) crank forces (Fig. 2) were recorded at 500 Hz using a Powerforce system (Radlabor, Freiburg, Germany). This is a measurement system mounted in between the pedal and the crank, and was previously described and validated by Stapelfeldt et al. (2017).

Full body kinematic data were captured at 250 Hz using a 12-camera optoelectronic setup (Qualisys, Gothenborg, Sweden) covering 98 for static and 77 markers for dynamic measurements (Fig. 3). A 3D kinematic method was chosen as previous research has shown its necessity for capturing valid joint angle data during cycling (Swart & Holliday, 2019). A skeletal model was built and tracked using a segment optimisation technique in Visual 3D (C-motion, Germantown, USA). The pelvis was modelled using markers on left and right anterior and posterior superior iliac spines, with the prediction of hip joint centres as described and validated by Bell et al. (1989; 1990). Joint angles were determined using a Cardan-Euler method (e.g. Davis et al., 1991; Engsberg & Andrews, 1987).

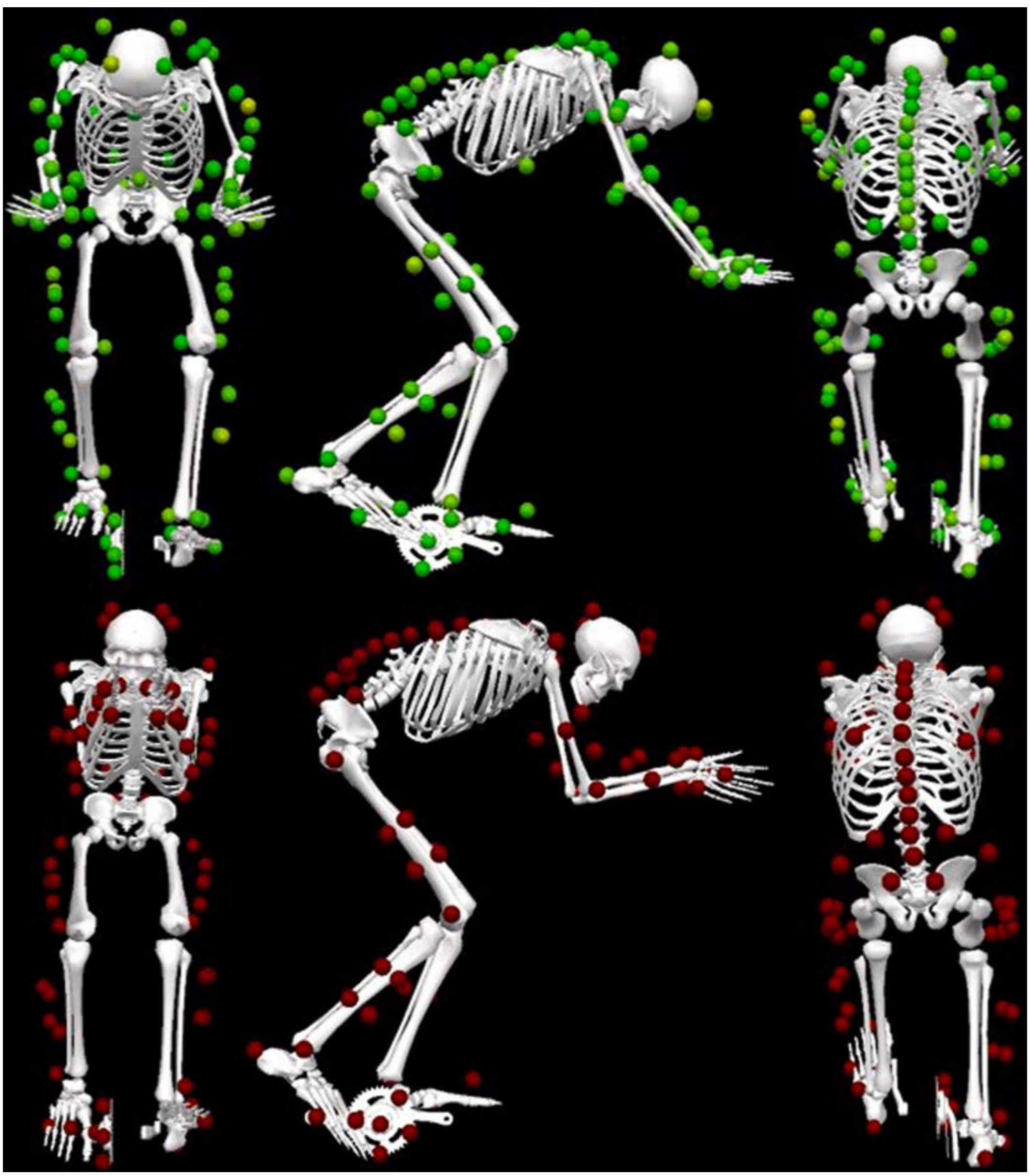

Fig. 3. Kinematic marker set viewed in ventral, sagittal and dorsal planes. Top panel reflect the full marker set used for skeletal modelling; bottom panels reflect the markers used for dynamic segment tracking.

Table 1
Demographics.

	N	Age (year)	Height (cm)	Body mass (kg)	Power		Cadence (rpm)
					Absolute (W)	Normalised ($W \cdot kg^{-1}$)	
Road	37	38.0 ± 11.7	177.6 ± 6.2	76.6 ± 8.9	276 ± 33	3.64 ± 0.54	96 ± 6
TT	19	36.9 ± 9.5	182.7 ± 5.0*	79.1 ± 7.9	281 ± 41	3.57 ± 0.50	93 ± 8

* Significant different from Road (F_{54} = 1.67, p = 0.003,$_s$=0.88).

Right leg data were resampled to 360 data points per revolution and averaged over the number of revolutions completed. Crank force data were filtered using a 4th order low-pass Butterworth filter at a 20 Hz cut- off frequency as per the manufacturer's recommendations. The same filter was applied to kinematic marker coordinate data, but with cut-off frequencies determined independently for each marker coordinate trajectory using a residual analysis - averaging at a cut-off frequency of 17 ± 3 Hz.

Crank angle (CA) data were used with Ft to calculate negative work (area under the negative portions of the Ft-CA curve), describing the amount of energy per crank revolution that resists propulsive motion. Mean absolute Fr was calculated by taking the average of the rectified signal, describing the radial force component that does not contribute to propulsive torque at the bottom bracket. To allow comparisons of the data across tests at different power outputs and cadences, crank force data were normalised. The negative work was expressed as a ratio to the net work done and crank force profiles were normalised to their mean Ft value (Jongerius et al., 2021). The IFE was defined as the ratio between the area under the Ft-CA curve and the area under the Ftot-CA curve (Coyle et al., 1991).

Joint angles were described as the degree of flexion, with all angles set to 0° at the anatomical reference position. For the evaluation of trunk kinematics, sagittal plane tilting of the pelvis relative to the global coordinate system was quantified as anterior pelvic tilting and trunk angle was defined as the angle between the horizontal and a line connecting the greater trochanter and glenohumeral joint. The linear position of the hip joint centre (Bell et al., 1989) was determined relative to the centre of the bottom bracket (BB) in the sagittal plane, with positive values describing positions in front and above the BB. These data were used to determine the effective seat tube angle (ESTA), as previously described by McDonald et al. (2022). A minor modification to its definition was made compared to McDonald et al. (2022), by defining ESTA as the angle between the horizontal and a line connecting the hip joint centre (rather than a point on the saddle) to the bottom bracket. This allowed tracking of dynamic changes in ESTA when saddle position remained unchanged.

Differences in kinetic and kinematic parameters between TT and Road groups were tested for statistical significance using independent t- tests for comparisons in PP, and using mixed model ANOVAs to compare the effects of group and standardised UP, DP and AP conditions. Statistical tests were carried out in SPSS 25 (IBM, USA) with an alpha level set at 0.05.

3. Results

Participants showed no significant differences in absolute and normalised power output, body mass or average cadence during the 20-minute test. Participants in the TT group were significantly taller than participants in the Road group (Table 1).

Details on PP configuration are provided in Table 2. The TT group showed a significantly more forward and slightly higher placed saddle than the Road group, resulting in a steeper seat tube angle. The handlebar was positioned significantly lower for the TT group, when expressed relative to the saddle position.

When riding in PP, the groups showed significant differences in kinematic but not kinetic parameters (Table 3). A significantly lower trunk

Table 2
Bike setup coordinates in PP for Road and TT groups. Saddle position is presented relative to Bottom Bracket with a negative horizontal value presenting a more backwards positioning. Handlebar position presented relative to the saddle, with a negative vertical value representing a lower position. Data for one road cyclist was missing.

		Road	TT	Between comparison
Saddle to bottom bracket	Horizontal (cm)	21.5 ± 1.7	17.3 ± 2.2	**$t_{53} = 7.76$, $p < 0.001$, $d_s = 2.20$**
	Vertical (cm)	68.2 ± 4.4	71.3 ± 3.1	**$t_{53} = -2.72$, $p = 0.009$, $d_s = -0.77$**
	Seat tube angle (°)	72.5 ± 0.8	76.3 ± 2.0	**$t_{53} = -10.12$, $p < 0.001$, $d_s = -2.87$**
Handlebar to saddle	Horizontal (cm)	79.9 ± 4.1	77.5 ± 9.7	$t_{53} = -1.29$, $p = 0.204$, $d_s = -0.36$
	Vertical (cm)	−2.9 ± 4. 1	−7.2 ± 4.5	**$t_{53} = 3.59$, $p = 0.001$, $d_s = 1.02$**

Table 3

Cycling biomechanics in PP for Road and TT groups. Note that due to their competitive focus, hand placement in PP is on aerobar extensions for TT and on a road handlebar for Road participants.

		Road	TT	Between comparison
Angular kinematics				
Trunk angle (°)		41.7 ± 5.8	16.3 ± 5.0	**t_{54} = 16.26, p < 0.001, d_s = 4.59**
Pelvic tilt (°)		20.0 ± 6.5	35.4 ± 7.0	**t_{54} = 8.19, p < 0.001, d_s = 2.31**
Hip (°)	Max	91.8 ± 5.8	97.5 ± 6.4	**t_{54} = -3.36, p = 0.001, d_s = -0.95**
	Min	42.9 ± 5.7	51.6 ± 6.5	**t_{54} = -5.17, p < 0.001, d_s = -1.46**
	RoM	48.9 ± 3.1	45.9 ± 3.1	**t_{54} = 3.42, p = 0.001, d_s = 0.97**
Knee (°)	Max	112.7 ± 4.3	112.0 ± 4.3	t_{54} = 0.60, p = 0.552, d_s = 0.17
	Min	32.3 ± 6.4	34.0 ± 6.1	t_{54} = -0.94, p = 0.354, d_s = -0.26
	RoM	80.4 ± 4.8	78.0 ± 3.9	t_{54} = 1.86, p = 0.068, d_s = -0.04
Ankle (°)	Max	12.6 ± 7.4	22.0 ± 7.4	**t_{53} = -4.51, p < 0.001, d_s = -1.28**
	Min	−8.6 ± 6.9	−2.1 ± 5.3	**t_{53} = -3.58, p = 0.001, d_s = -1.02**
	RoM	20.6 ± 6.7	24.4 ± 5.6	**t_{53} = -2.14, p = 0.037, d_s = -0.61**
Linear kinematics				
Horizontal hip joint position (cm)		−18.4 ± 4.3	−8.1 ± 3.9	**t_{54} = -8.71, p < 0.001, d_s = -2.46**
Vertical hip joint position (cm)		80.4 ± 4.5	83.7 ± 3.0	**t_{54} = -2.81, p = 0.007, d_s = -0.79**
Effective seat tube angle (°)		77.2 ± 2.8	84.5 ± 2.7	**t_{54} = 9.47, p < 0.001, d_s = 2.67**
Mechanical effectiveness				
IFE (%)		47.8 ± 6.1	49.1 ± 6.2	t_{54} = -0.73, p = 0.468, d_s = -0.21
Negative work (Normalised)		0.17 ± 0.08	0.17 ± 0.08	t_{54} = -0.34, p = 0.732, d_s = -0.10
Rectified mean radial forces (Normalised)		1.36 ± 0.21	1.32 ± 0.23	t_{54} = 0.64, p = 0.528, d_s = -0.18

Table 4
Mechanical effectiveness parameters across standardised positions and cyclist groups.

		Road	TT	Within	Between	Interaction
IFE (%)	UP	48.0 ± 6.8	51.0 ± 6.2	*Main effect* $F_{2,53} = 15.29$, $p < 0.001$, $\eta_p^2 = 0.22$ *Post hoc* UP > AP, DP > AP	*Main effect* $F_{2,53} = 5.31$, $p = 0.025$, $\eta_p^2 = 0.09$ *Post hoc* TT > Road	*Main effect* $F_{2,53} = 4.32$, $p = 0.016$, $\eta_p^2 = 0.07$ *Post hoc* TT > Road @ DP & AP TT ns @ all positions Road UP > DP, UP > AP, DP > AP
	DP	46.3 ± 6.0	51.0 ± 6.8			
	AP	45.3 ± 6.2	50.0 ± 6.9			
Negative work (Normalised)	UP	0.17 ± 0.09	0.15 ± 0.08	*Main effect* $F_{2,53} = 11.35$, $p < 0.001$, $\eta_p^2 = 0.174$ *Post hoc* UP < DP, UP < AP, DP < AP	*Main effect* $F_{2,53} = 2.28$, $p = 0.137$, $\eta_p^2 = 0.04$	*Main effect* $F_{2,53} = 2.66$, $p = 0.075$, $\eta_p^2 = 0.05$
	DP	0.19 ± 0.08	0.15 ± 0.09			
	AP	0.20 ± 0.09	0.16 ± 0.09			
Rectified mean radial forces (Normalised)	UP	1.36 ± 0.24	1.25 ± 0.22	*Main effect* $F_{2,53} = 21.23$, $p < 0.001$, $\eta_p^2 = 0.28$ *Post hoc* UP < DP, UP < AP, DP < AP	*Main effect* $F_{2,53} = 5.51$, $p = 0.023$, $\eta_p^2 = 0.09$ *Post hoc* TT < Road	*Main effect* $F_{2,53} = 4.52$, $p = 0.013$, $\eta_p^2 = 0.08$ *Post hoc* TT < Road @ DP & AP TT ns @ all positions Road UP < DP, UP < AP, DP < AP
	DP	1.42 ± 0.22	1.25 ± 0.24			
	AP	1.46 ± 0.23	1.29 ± 0.26			

ns: non-significant.

angle and more anterior pelvic tilt was observed in the TT group. Hip and ankle angles were significantly more flexed with a smaller range of motion (RoM). Knee angle data showed no significant differences between the groups. In addition, the linear hip joint position relative to the bottom bracket was significantly further forwards (+10.3 cm) and higher (+3.3 cm) in the TT group compared to the Road group. This resulted in the TT group riding with a significantly steeper ESTA. Parameters of mechanical effectiveness revealed no significant differences between TT and Road groups when riding in PP with average IFE scores of 49.1 ± 6.2% and 47.8 ± 6.1%, respectively.

Comparisons of crank force data for the standardised UP, DP and AP conditions revealed that the TT group produced significantly higher IFE and lower radial forces across the three positions (Table 4). Within- subject testing showed that smaller trunk angle positions resulted in significantly reduced IFE and increased negative work and radial forces, although the effects on IFE and radial forces were only significant for the Road group as indicated by a significant group by position interaction effect.

Kinematic data showed the trunk angle to be significantly lowered and anterior pelvic tilting significantly increased for both groups when changing from UP, to DP, to AP (Table 5). The hip was significantly more flexed and moved through a smaller RoM. Small (<1°) but significant differences in peak knee extension and RoM were also observed. Greater effects were seen for the ankle joint as it became significantly more dorsiflexed for lower trunk angle positions. Significant between-group differences were only seen for the hip and ankle angles, which were more extended and dorsiflexed in the TT group. No significant group by position interaction effects were found in the joint angle parameters tested.

Whilst the saddle position remained unchanged between the three standardised positions, linear kinematics revealed that the linear position of the hip joint responded significantly to positional changes (Table 6). The joint translated significantly forwards and downwards when moving from UP to DP to AP, with the downward movement only significant for the TT group. This resulted in significantly steeper ESTA for lower trunk positions. Between-group comparisons showed the TT group's hip position was further forwards and higher over the three tested positions, which agrees with the different saddle placements in PP.

4. Discussion

The current research systematically evaluated the effects of positional changes on cycling biomechanics across TT and Road trained cyclists. It was shown that, when riding in their PP, TT trained cyclists adopted a significantly different riding position compared to their Road counterparts. In addition to the expected increased trunk flexion, anterior pelvic tilting and hip flexion, ankle dorsiflexion was also increased and a greater RoM of the hip and ankle joints were adopted. Furthermore, TT cyclists position their hip joint significantly further forwards and slightly higher in relation to the BB. Despite these kinematic differences between the groups, no significant differences were observed in mechanical effectiveness parameters between the two groups. These data suggest force application was equally effective for both groups, despite their different cycling position.

When comparing across the standardised cycling positions, this study is the first to identify a significant effect of position on mechanical effectiveness for both groups, indicating a less advantageous application of forces at the foot/pedal interface when lowering trunk position in cycling. However, these positional effects were different between TT and Road trained cyclists. Whilst both groups showed a significant increase in negative work when moving from UP to DP to AP, the increased magnitude of Fr was only significant for Road cyclists, as was the corresponding reduction in IFE. It appears that both groups were negatively affected by a change towards lower trunk positions, but the TT group were able to reduce its impact.

Table 5
Sagittal kinematics across standardised positions and cyclist groups.

			Road	TT	Within	Between	Interaction
Trunk angle (°)		UP	39.3 ± 3.9	39.6 ± 3.1	*Main effect* $F_{1.8,53} = 852.43$, $p < 0.001$, $\eta_p^2 = 0.94$*	*Main effect* $F_{2,53} = 0.58$, $p = 0.450$, $\eta_p^2 = 0.01$	*Main effect* $F_{1.8,53} = 1.49$, $p < 0.231$, $\eta_p^2 = 0.03$*
		DP	29.2 ± 2.7	30.4 ± 2.4			
		AP	23.8 ± 2.5	23.8 ± 1.7	*Post hoc:* UP > DP, UP > AP, DP > AP		
Pelvic tilt (°)		UP	21.2 ± 4.6	22.1 ± 6.3	*Main effect* $F_{1.7,53} = 345.81$, $p < 0.001$, $\eta_p^2 = 0.87$*	*Main effect* $F_{2,53} = 0.32$, $p < 0.574$, $\eta_p^2 = 0.01$*	*Main effect* $F_{1.7,53} = 0.60$, $p < 0.521$, $\eta_p^2 = 0.01$*
		DP	26.7 ± 4.9	27.9 ± 6.1			
		AP	30.1 ± 4.9	30.6 ± 6.1	*Post hoc:* UP < DP, UP < AP, DP < AP		
Hip joint angle (°)	Max	UP	92.6 ± 4.8	87.7 ± 7.3	*Main effect* $F_{1.8,53} = 250.29$, $p < 0.001$, $\eta_p^2 = 0.83$*	*Main effect* $F_{2,53} = 10.30$, $p = 0.002$, $\eta_p^2 = 0.16$	*Main effect* $F_{1.8,53} = 0.44$, $p = 0.621$, $\eta_p^2 = 0.01$*
		DP	97.4 ± 5.1	92.3 ± 6.7			
		AP	99.6 ± 5.3	94.2 ± 6.7	*Post hoc:* UP < DP, UP < AP, DP < AP	*Post hoc* TT < Road	
	Min	UP	43.9 ± 4.7	40.6 ± 6.7	*Main effect* $F_{1.8,53} = 218.92$, $p < 0.001$, $\eta_p^2 = 0.81$*	*Main effect* $F_{2,53} = 4.96$, $p = 0.030$, $\eta_p^2 = 0.09$	*Main effect* $F_{1.8,53} = 0.27$, $p = 0.744$, $\eta_p^2 = 0.01$*
		DP	49.0 ± 5.4	45.6 ± 6.1		*Post hoc*	
		AP	51.5 ± 5.6	47.8 ± 6.5	*Post hoc* UP < DP, UP < AP, DP < AP	TT < Road	
	RoM	UP	48.7 ± 3.0	47.1 ± 3.1	*Main effect* $F_{1.8,53} = 10.28$, $p < 0.001$, $\eta_p^2 = 0.16$*	*Main effect* $F_{2,53} = 3.91$, $p = 0.053$, $\eta_p^2 = 0.07$	*Main effect* $F_{1.8,53} = 0.02$, $p = 0.973$, $\eta_p^2 < 0.00$*
		DP	48.4 ± 2.9	46.7 ± 2.9	*Post hoc*		
		AP	48.1 ± 3.0	46.4 ± 3.1	UP > DP, UP > AP		

			Road	TT	Within	Between	Interaction
Knee joint angle (°)	Max	UP	112.8 ± 4.5	111.7 ± 4.1	*Main effect* $F_{2,53} = 3.007$, $p = 0.054$, $\eta_p^2 = 0.05$	*Main effect* $F_{2,53} = 0.70$, $p = 0.407$, $\eta_p^2 = 0.01$	*Main effect* $F_{2,53} = 0.03$, $p = 0.974$, $\eta_p^2 < 0.00$
		DP	113.0 ± 4.5	112.0 ± 4.2			
		AP	113.2 ± 4.7	112.2 ± 4.4			
	Min	UP	32.6 ± 6.6	32.3 ± 5.4	*Main effect* $F_{1.8,53} = 6.39$, $p = 0.003$, $\eta_p^2 = 0.11$* *Post hoc* UP>DP, UP>AP	*Main effect* $F_{2,53} = 0.01$, $p = 0.917$, $\eta_p^2 < 0.00$	*Main effect* $F_{1.8,53} = 0.11$, $p = 0.876$, $\eta_p^2 < 0.00$*
		DP	33.3 ± 7.0	33.1 ± 5.2			
		AP	33.5 ± 7.5	33.5 ± 6.2			
	RoM	UP	80.2 ± 4.8	79.4 ± 3.3	*Main effect* $F_{1.7,53} = 6.51$, $p = 0.003$, $\eta_p^2 = 0.108$* *Post hoc* UP>DP, UP>AP	*Main effect* $F_{2,53} = 0.456$, $p = 0.502$, $\eta_p^2 = 0.01$	*Main effect* $F_{1.7,53} = 0.161$, $p = 0.821$, $\eta_p^2 < 0.01$*
		DP	79.7 ± 4.8	78.8 ± 3.2			
		AP	79.7 ± 5.2	78.7 ± 4.1			
Ankle joint angle (°)	Max	UP	13.2 ± 7.4	19.6 ± 8.8	*Main effect* $F_{1.5,53} = 19.23$, $p < 0.001$, $\eta_p^2 = 0.27$* *Post hoc* UP<AP, DP<AP	*Main effect* $F_{2,53} = 8.44$, $p = 0.005$, $\eta_p^2 = 0.14$ *Post hoc* TT > Road	*Main effect* $F_{1.5,53} = 0.93$, $p = 0.375$, $\eta_p^2 = 0.02$*
		DP	13.7 ± 7.4	20.5 ± 8.0			
		AP	15.2 ± 7.6	21.2 ± 7.8			
	Min	UP	−7.9 ± 7.4	−4.8 ± 5.8	*Main effect* $F_{1.7,53} = 9.72$, $p < 0.001$, $\eta_p^2 = 0.16$* *Post hoc* UP<DP, UP<AP	*Main effect* $F_{2,53} = 2.11$, $p = 0.152$, $\eta_p^2 = 0.04$	*Main effect* $F_{1.7,53} = 0.40$, $p = 0.643$, $\eta_p^2 = 0.01$*
		DP	−6.9 ± 7.8	−3.7 ± 5.2			
		AP	−6.3 ± 8.6	−3.6 ± 5.1			
	RoM	UP	21.1 ± 6.8	24.4 ± 7.2	*Main effect* $F_{1.6,53} = 2.60$, $p = 0.090$, $\eta_p^2 = 0.05$*	*Main effect* $F_{2,53} = 3.21$, $p = 0.079$, $\eta_p^2 = 0.06$	*Main effect* $F_{1.6,53} = 0.13$, $p =$, $\eta_p^2 < 0.01$*
		DP	20.6 ± 6.4	24.2 ± 6.9			
		AP	21.5 ± 7.0	24.8 ± 6.0			

* Adjusted to Huynh-Feldt due to significant sphericity.

Table 6
Hip joint position relative to the bottom bracket across standardised positions and cyclist groups.

		Road	TT	Within	Between	Interaction
Horizontal hip joint position (cm)	UP	−18.0 ± 4.5	−12.5 ± 3.3	*Main effect* $F_{2,53} = 35.76$, $p < 0.001$, $\eta_p^2 = 0.40$ *Post hoc* UP < DP, UP < AP, DP < AP	*Main effect* $F_{2,53} = 24.52$, $p < 0.001$, $\eta_p^2 = 0.32$ *Post hoc* TT > Road	*Main effect* $F_{2,53} = 0.79$, $p = 0.456$, $\eta_p^2 = 0.02$
	DP	−16.8 ± 4.7	−10.8 ± 3.4			
	AP	−16.0 ± 5.3	−9.7 ± 3.4			
Vertical hip joint position (cm)	UP	80.3 ± 4.6	84.1 ± 3.0	*Main effect* $F_{1.8,53} = 9.24$, $p < 0.001$, $\eta_p^2 = 0.15$* *Post hoc* UP > DP, UP > AP	*Main effect* $F_{2,53} = 9.73$, $p = 0.003$, $\eta_p^2 = 0.16$ *Post hoc* TT > Road	*Main effect* $F_{1.8,53} = 5.58$, $p = 0.007$, $\eta_p^2 = 0.10$* *Post hoc* TT > Road @ all positions <u>TT:</u> UP > DP, UP > AP <u>Road:</u> ns @ all positions
	DP	80.3 ± 4.7	83.9 ± 3.0			
	AP	80.2 ± 4.7	83.9 ± 3.0			
Effective seat tube angle (°)	UP	77.4 ± 2.7	81.6 ± 2.2	*Main effect* $F_{2,53} = 37.53$, $p < 0.001$, $\eta_p^2 = 0.42$ *Post hoc* UP < DP, UP < AP. DP < AP	*Main effect* F2,53 = 32.81, P < 0.001, $\eta_p^2 = 0.38$ *Post hoc* TT > Road	*Main effect* $F_{2,53} = 0.62$, $p = 0.538$, $\eta_p^2 = 0.01$
	DP	78.3 ± 3.0	82.6 ± 2.3			
	AP	78.9 ± 3.3	83.4 ± 2.3			

* Adjusted to Huynh-Feldt due to significant sphericity.
ns: non-significant.

There is a clear practical relevance in further investigating these different responses, as maintaining better mechanical effectiveness in more aerodynamic positions could reduce some of the performance decreases reported in previous studies (Ashe et al., 2003, Fintelman et al., 2015a). An analysis of sagittal kinematics on the full cohort showed that lower trunk positions were achieved by increasing anterior pelvic tilt. Given the close relationship between pelvic tilting and hip angle, it is no surprise that a significant increase in hip flexion occurred. Interestingly, the magnitude of increased pelvic tilt (+8.9 and + 8.5° for Road and TT, respectively) between UP and AP exceeded the corresponding increased peak hip flexion (+7.0 and + 6.5° for Road and TT, respectively). The response seen in hip flexion angle is therefore lower than what would have been expected to result from the observed increase in anterior pelvic tilt.

This apparent discrepancy can be explained by evaluating data for knee and ankle angles and linear hip position. The increased ankle dorsiflexion angle observed for the lower trunk angle positions could have facilitated the hip to remain relatively extended. However, the kinematic patterns for the knee joint are remarkably similar across groups and conditions, with significant differences in peak angles and RoM between UP and AP conditions not exceeding 1°. This creates a conflict as an increase in hip flexion combined with an increase in ankle dorsiflexion for a fixed knee angle is mechanically impossible if the position of the hip joint relative to the pedal stays the same. As participants used clipless pedals with tight fitting shoes, there will have been very little if any movement between the distal end of the foot and the pedal. This suggests that the hip joint must have moved relative to the pedal for the reported kinematic changes to be achievable. Indeed, the hip joint centre shows a significant forward translation when moving to lower trunk angle positions, facilitating the observed joint angle responses. In monitoring cycling kinematics, it has previously been considered acceptable to assume that the linear hip joint position is fixed for a set saddle position (Martin et al., 2007). The results from this study contest this and instead suggest a potential pivotal role for acute changes in linear hip placement to cope with positional changes.

The hip and ankle joint angle responses align with a wider trend seen in cycling research. Savelberg et al. (2003) have previously shown combined changes in hip flexion and ankle dorsiflexion with little response at the knee joint across different recumbent cycling configurations. Bini et al. (2010) also showed the ankle and hip kinematics to be the first affected in a fatiguing protocol and Ferrer-Roca et al. (2014) reported the greatest effects for the ankle joint following small saddle height changes.

It appears that kinematic responses at the ankle and hip joint dominate the knee joint alterations in cycling. It could be argued that this is to allow the mono-articular knee extensor muscles to maintain a more favourable position on the length-tension curve, preserving force producing capabilities. However, previous research by Sanderson et al. (2003) suggested that a change in the ankle angle can directly influence the orientation of the force vector at the foot/pedal interface. The observed changes therefore might be favourable for knee extensor muscle functioning but could also result in a compromised mechanical effectiveness due to ankle angle changes.

This link between the observed kinematic coping strategy and mechanical effectiveness can explain how TT cyclists outperformed Road cyclists in maintaining mechanical effectiveness with positional changes. Data on PP conditions show the TT group to ride with relatively more forward positioned hip joints and dorsiflexed ankle joints, while utilising a greater ankle RoM throughout the pedal revolution. Crucially, while the TT and Road cyclists showed a similar level of anterior pelvic tilt across the UP, DP and AP positions, the combination of a similar pelvic tilt and a more anterior position of the hip joint explain why the TT cyclists displayed a more extended hip joint throughout all positions. The TT cyclist's hip placement seems pivotal in allowing them group to cope better with the positional changes, as they can maintain an ankle angle closer to that observed in PP and reduce the consequential effects on force application at the pedal.

These results add to any notion that prolonged training in a dedicated AP setup can result in position-specific adaptations. It shows that kinematic differences in linear hip positioning play a critical role in mitigating acute responses to positional changes. The current study evaluated cycling biomechanics at the cadence and power output achieved during a self-paced 20-minute maximum effort. This was purposefully done to reflect an intensity typical for a UK 10-mile TT event and improve the ecological validity of the outcomes. However, previous studies have clearly identified the impact of power output and cadence on joint kinematics and force application in cycling (Patterson & Moreno, 1990; Sanderson et al., 1991; Rossato et al., 2008). The results from this study should therefore be replicated in a wider range of testing conditions to ensure that the outcomes are fully generalisable to a wider range of cycling competitions. These outcomes show the importance of reporting comprehensive kinematic descriptions of experimental conditions in future studies, in order to avoid differences in bike positioning confounding the results when comparing interventions or investigating training effects.

There are several important implications for professionals working to optimise cyclists' positions for events where AP setups are advantageous. Lowering the trunk can have detrimental effects on the physical performance of the cyclist. This study showed that by observing a significant decrease in mechanical effectiveness. The more forward positioned hip joint preferred by TT cyclists seemed to allow for better compensation of the kinematic changes induced by moving to AP, and mitigated the negative effects in force application. This suggests a critical role for hip and saddle placement in coping with the effects of positional changes. This was further shown by the acute change in linear hip placement when changing cycling position. While further research is needed to confirm the causal relationships, the current study provides practitioners with an opportunity to mitigate the negative mechanical effectiveness effects with confidence, by facilitating a more anteriorly positioned hip joint through adjustments in saddle placement.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2022.111103.

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