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The Influence of Bicycle Geometry on Time-Trial Positioning Kinematics and Markers of Performance

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Abstract: Studies have previously documented how changes in cycling body kinematics are related to submaximal energetics and power output, as well as cycling performance, but few have focused specifically on how body kinematics will vary with changes in bicycle geometry. This study sought to describe kinematic changes resulting from the systematic change of several bicycle geometry variables: Trunk angle ("low" and "high" positions), seat-tube angle (76° and 80°), saddle tilt angle (0° to -10°), saddle sitting position (middle or nose), as well as two types of saddles. *Methods*: Well-trained cyclists were kinematically evaluated across specific combinations of geometry variables using a modified cycle ergometer at a standard relative power. Standard two-dimensional sagittal-view kinematics from the left side were used to summarize a collection of kinematic variables: Trunk angle, hip angle (HA), knee angle, pelvic tilt angle, and two "composite" angles called body position and pelvic position (PP). Finally, each trial was also evaluated for frontal area (FA; m^2) from stationary digital photography. Data were evaluated using repeated measures ANOVA (α=0.05) to evaluate change in kinematics between trials, as well as regression analysis to determine predictability of performance markers (HA and FA) from the collection of geometry and kinematic variables. *Results:* Changing trunk angle had the greatest impact on other kinematic variables, while saddle type had no influence. Regression showed that geometry variables could explain 75-85% of the variability in either HA or FA, while 78-79% of the variation in HA and 83-84% of FA was explained by PP alone. *Conclusions:* The composite kinematic measure PP was generally a better predictor of both HA and FA than any combination of geometry variables. These results can serve as a starting point for understanding the interactions between bicycle geometry and body kinematics, both of which are important determinants of power generation and aerodynamic drag.

Key Words: Aerodynamic drag, Body position, Cycling, Ergometry.

Dan Heil is a professor in applied exercise physiology in the Department of Health and Human Development at Montana State University and has been awarded Fellow status by the American College of Sports Medicine. Dr. Heil's research focuses on determinants of human health, energy expenditure, and work performance during free-living, recreational, occupational, and sport-related activities. As such, his research often includes the use of wearable electronic monitoring devices, novel analytical strategies, as well as mathematical and statistical modelling. Dr. Heil's research interests are often inspired by his own personal interest and participation in a variety of sports that include triathlons, cross country skiing, open water swim racing, and taekwondo.

Robert Pickels is a Physiologist conducting Advanced Development with the cycling apparel brand PEARL iZUMi in Louisville, Colorado. His research interest lies at the interface of cyclists and the environment they ride in. This ranges from the effect of apparel components, constructions and materials on both perception and thermoregulation to the mechanical interface between a rider and weightbearing structures. Formally Robert was the Lead Physiologist at the renowned Boulder Center for Sports Medicine. Here he applied his knowledge to consulting professional athletes, recreational athletes and medical patients alike. Additionally, he engaged in both physiological and biomechanical research with a focus on product development and validation. Currently living in Boulder Colorado, Rob is an active cyclist himself and enjoys coaching junior cyclocross riders.

Introduction

Optimization of time-trial cycling performance over long distances represents a tightly coupled relationship between maximizing sustainable physiological power output while minimizing the net resistance to external forces [1-2]. It is generally accepted that the success of this relationship depends highly upon a properly fitted bicycle to the cyclist, as well as knowledge of how the resulting fit will influence outdoor cycling performance. There have been numerous attempts by researchers to study the intricacies of this relationship within the confines of a laboratory setting, under controlled outdoor settings, as part of simulated or actual cycling races, as well as with use of statistical and mathematical modeling strategies. Most of these studies, however, are forced to focus on the systematic variation of one or two variables of interest because the potential degrees of freedom to fitting a cyclist to a bicycle are enormous relative to other sporting activities. Clearly, the systematic study of the functional interaction between a cyclist and bicycle is complex, difficult to control in laboratory settings, and even more difficult to extrapolate to field settings.

To study this complex interaction of cyclist and bicycle, researchers often attempt to control as many bicycle geometry variables possible while allowing only one or two other variables to vary in a predictable manner. *Geometry variables* are defined by this paper as any adjustable bicycle fit parameter that influences any one of the three contact points (i.e., the pedals, saddle, and handlebars) between the cyclist and the bicycle. Some common geometry variables studied by researchers for road and/or time-trial bicycling include saddle height [3], crank length [4-6], shape of the front chain ring [7-8], seat-tube angle (STA) [9-11], as well as saddle design [12-13]. In contrast to geometry variables, other researchers have focused on body kinematics and/or performance outcomes that result from cyclists interacting with a bicycle or cycle ergometer with a fixed geometry. For the present study, *kinematic variables* are those that define how the body interacts with the bicycle or cycle ergometer. One of the most common bicycling-related kinematic variables studied has been trunk angle (TA), which has also been referred to as trunk or body position [10, 11, 14-26]. While it is not always common, some studies have also combined the study and/or reporting of both geometry and kinematic variables to more accurately define the nature of interaction between the cyclist and bicycle. Heil et al. [9], for example, systematically varied a single bicycle geometry variable (seat-tube angle) while keeping all other geometry variables constant to measure the resulting influence on submaximal physiological outcomes (i.e., steady-state oxygen uptake and heart rate) and sagittal-view kinematics (i.e., mean trunk, hip, knee, and ankle angles).

While many of the above-mentioned studies were well designed and able to provide some definitive conclusions with reference to the cyclist/bicycle interaction, very few provide extensive kinematic evaluations. These kinematic evaluations allow the reader to more directly compare the results from different studies since a primary outcome of the cyclist/bicycle interaction is the kinematics. Several studies, for example, have related changes in submaximal physiological measures when cycling to changes in mean hip angle (HA) [9-11], while mean knee angle seemed indifferent despite the large changes in seat-tube angles. Thus, these studies were able to relate changes in bicycle geometry to subsequent changes in body kinematics, which then helped explain changes in physiological parameters. Interestingly, with the exception of studies focused on saddle design and comfort [12], the use of pelvic tilt angle (PTA) as a kinematic marker is almost non-existent in cycling studies. This seems unusual because the hip extensor muscles responsible for power production during cycling all originate on the pelvis. Thus, the inclusion of PTA as a kinematic marker may be better than HA or TA for explaining changes in observed physiological and performance parameters.

Despite the extensive evaluations of both bicycle geometry and body kinematic variables related to bicycle fit and performance, rarely has the number of varied parameters been greater than two. In addition, many of the previously mentioned studies do not report critical information about the cyclist and bicycle interaction such as where the hands are placed on the handlebars, whether the elbows could bend or not, or where on the saddle that cyclists were required to sit during testing. Each of these factors mentioned has the potential to influence the resulting kinematic variables without any change in bicycle geometry. Thus, these unreported issues may also have the potential to influence any subsequent physiological or performance outcome measures. Whether these variables were not controlled during testing or simply not reported in the published papers cannot be determined, but the net effect is a collection of bicycling-related research literature that is difficult to understand and summarize by researchers and non-researchers alike.

Clearly, there is a large gap in the research literature that extensively relates the complex interaction of the cyclist and bicycle to kinematic, physiological, or performance outcome measures. Thus, the primary goal of the present study was to kinematically describe the cyclist/bicycle interaction through a wide range of bicycle geometry and body kinematic variables that are commonly focused upon when fitting a cyclist to a bicycle. Further, because of the number of trials required to systematically compare multiple levels of many variables; this study was broken into two separate research projects. The primary outcome of these evaluations was a summary of kinematic variables that described the kinematic consequence of each combination of geometry variables. Included within these sagittal-view analyses were kinematics common to previous cycle ergometer studies, as well as several new "composite" kinematic measures. A secondary goal of this study was to relate the geometry and kinematic variables to mean hip angle (HA) and projected frontal area (FA) since both have been shown to impact either submaximal or maximal markers of cycling performance [10,27-28]. In accomplishing both primary and secondary goals, the results of this study should serve as a platform for further evaluations of the interaction between cyclists and their bicycles.

Methods

2.1 Procedures

Cyclists and triathletes experienced with training and racing with aerobars were recruited for either one of two studies, hereafter referred to as Project I and Project II. In addition, different cyclists were recruited for each Project to improve the generalizability of the findings. All cyclists completed a health screening questionnaire as well as read and signed an Informed Consent Document approved by the Institutional Review Board of Montana State University. Next, cyclists completed a series of submaximal trials specific to Project I or Project II. The focus of Project I was to evaluate two levels each of three geometry variables (STA, the brand of saddle, and the fore-aft sitting position on the saddle) at two levels a single kinematic variable (TA) (16 trials total). The focus of Project II, in contrast, was to evaluate the same two levels of the three geometry variables from Project I (STA, the brand of saddle, and the fore-after sitting position on the saddle) across three levels of a fourth geometry variable – i.e., saddle tilt – while maintaining a constant TA (24 trials total).

For both Projects, a preliminary submaximal trial was used to determine an appropriate power output for subsequent testing. Specifically, the cyclists used their own time-trial bicycle mounted to a stationary trainer to perform a 5-minute self-paced warm-up. Next, a power output equivalent to 70-80% of age-predicted maximum heart rate (i.e., 70-80% of 220-age) while pedaling 90 RPM was determined for the subsequent testing trials. This strategy was designed to provide a similar relative cycling intensity between cyclists. For the next set of submaximal trials, the geometry dimensions for each cyclist's time-trial bicycle were transferred to a cycle testing ergometer (Figure 1). The dimensions transferred to the ergometer included crank length, seat height, seat-to-handlebar distance, as well as aero handlebar height relative to the bicycle seat. The remaining ergometer geometry parameters were then set according to whether the cyclist was participating in Project I or II.

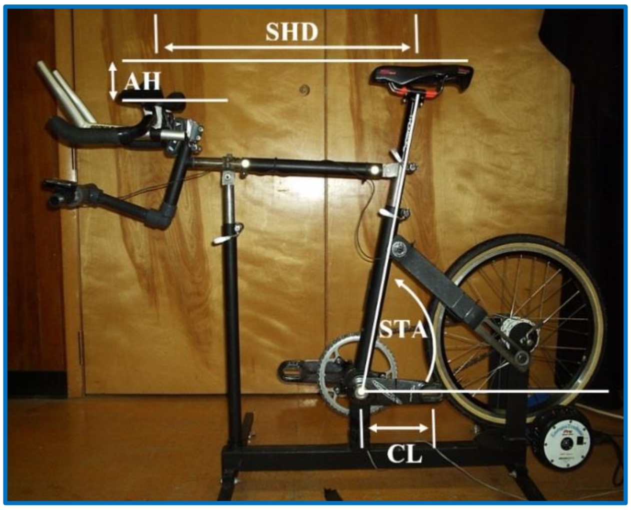

Figure1. Illustration of several geometry variables transferred to the testing ergometer from each each cyclist's time-trial bicycle: Seat-tube angle (STA), seat-to-handlebar distance (SHD), aerobar height (AH), and crank length (CL).

For Project I, cyclists completed a total of 16 different preplanned trials as outlined in Table 1. Specifically, four parameters were tested at all possible combinations for a total of 16 different submaximal trials: [Two STAs (76° and 80°)] x [two TAs ("low" and "high positions)] x [two saddle models] x [two saddle sitting positions (middle of the saddle versus nose of the saddle)] = 16 trial combinations.

For Project II, cyclists completed a total of 24 preplanned trials (Table 1) that included all combinations of four parameters: [Two STAs (76° and 80°)] x [two saddle models] x [two saddle sitting positions (middle of the saddle versus nose of the saddle)] x [three saddle tilt angles of -10°, -5°, 0°] = 24 trial combinations. Each one of the above listed variables, as well as the ranges through which they were evaluated, are common variables of interest when fitting a cyclist to a bicycle for time-trial racing. For both Projects I and II, individual cyclists were randomly assigned to a counterbalanced order of testing to help control for possible order effects.

The cycling ergometer used for all testing was a modified Serotta Size-Cycle™ (pre-year 2000 model; Serotta Bicycles, Saratoga Springs, NY USA) to allow quick changes between positions, as well as to increase the ergometer's stability for cycle performance testing. The primary advantage of the ergometer for the present study was the ability to change both STA and handlebar position quickly between trials while maintaining seat height (Figure 1). The ergometer setup for the first testing trial involved transferring the measures described previously (crank length, seat height, seat-to-handlebar distance, as well as aero handlebar height relative to the bicycle seat) from the cyclist's bicycle to the ergometer. Next, using a swiveling bottom bracket that locked into fixed positions, the STA was set to the first condition, which was then followed by the positioning of the handlebars and then the tilt of the saddle. When positioning the handlebars, care was also taken to ensure that both the upper arms 01and forearms were in the same relative positions for each trial (as shown in Figure 2). Finally, the reference to "low" and "high" TA positions for

Project I was purely a function of how the handlebar position was set with the ergometer. Specifically, the ergometer easily allowed for gross placement of the handlebars (e.g., near horizontal torso position), but creating specific predetermined TAs was not possible. Thus, the "low" TA was simply the handlebar placement that created a slightly positive TA (i.e., 0-10° TA), while the "high" TA was a result of a handlebar placement that resulted in a much more upright TA (i.e., 20-30° TA). Subsequent trials required only two minutes (at most) to change the geometry variables as needed for the next trial.

For both Projects, retro-reflective markers were then placed on the cyclist's left side corresponding to the following anatomical landmarks (Figure 2A): Acromion process (M1), iliac crest (M2), posterior superior iliac spine (PSIS; M3), anterior superior iliac spine (ASIS; M4), the greater trochanter (M5), the knee joint (M6), the lateral malleolus (M7), and the ergometer's crank axis (M8). These markers, in turn, were used to define body segments corresponding to the trunk (M1 to M2), the pelvis (M3 to M4), the thigh

(M5 to M6), and the lower leg (M7 to M8). These segments, in combination with other parameters, were then used to define four common sagittal-view angles: Trunk angle (TA), pelvic tilt angle (PTA), hip angle (HA), and knee angle (KA)), as well as two composite angles (body position (BP) and pelvic position (PP)) (Figures 2B-2D). The composite angles are those that include markers from both the body of the cyclist and the cycle ergometer. As such, it was thought a priori that one or both composite angles may be more sensitive markers of change when multiple geometry variables were changed simultaneously (such as for the current study). Definitions for all kinematic outcome measures are provided in Table 1.

Table 1. Definitions for both independent and dependent variables of interest for Projects I and II. Independent variables are those variables purposely varied as part of the study design, whereas dependent variables are those variables evaluated for change in response to changes in one or more of the independent variables.

Variables Of Interest	Definition and/or Description of Variables
<u>Independent Variables</u>	
Trunk Angle	TA (degrees) - The included angle between the trunk segment and a horizontal line through the iliac crest (Figure 2B).
Seat-Tube Angle	STA (degrees) - The included angle between a line linking the crank axis and the center of the saddle with another horizontal line through the crank axis (Fig 1).
Saddle Design	Refers to the use of either the Adamo (Figure 3A) or Profile saddles (Fig 3B).
Saddle Position	Refers to how the cyclists are told to sit on the ergometer saddle. Specifically, cyclists were told to site either in the middle of the saddle (i.e., conventional sitting position for any saddle) or the nose of the saddle (commonly adopted for time-trial positioning).
Saddle Tilt Angle	Refers to the position of the saddle nose relative to the back end of the saddle. A level saddle tilt angle (0º) indicated that the saddle nose was level with the back end, while a negative tilt angle indicated that the nose was dropped below the horizontal.
<u>Dependent Variables</u>	
Hip Angle	HA (degrees) - The included angle between the thigh segment and another segment between the acromion process and the greater trochanter (Figure 2C). This is the first of two performance markers evaluated.
Pelvic Tilt Angle	PTA (degrees) – The angle between the pelvis segment and a horizontal line through the posterior superior iliac spine (PSIS) (Fig 2B).
Knee Angle	KA (degrees) – The included angle between the thigh and lower leg segments (Fig 2B).
Body Position	BP (degrees) – The included angle between a segment between the acromion process and the greater trochanter, and another segment between the great trochanter and the crank axis (Figure 2C). This is one of two composite

	kinematic measures evaluated.
Pelvic Position	PP (degrees) - The included angle between a segment between the acromion process and the posterior superior iliac spine (PSIS), and another segment between the great trochanter and the crank axis (Fig 2D). This is the second of two composite kinematic measures evaluated.
Frontal Area	FA (m^2) – Refers to the projected frontal area of the cyclists in the frontal plane as determined from digital photography. This is the second of two performance markers evaluated.

Once the ergometer was ready, the cyclist completed a 2-minute warm-up while pedaling 90 RPM and adopting the test position.

Figure 2. Illustration of kinematic variables assessed. A total of eight reflective markers (M1-M8 emphasized in yellow; A) were used to identify multiple body segments which were then used to define a collection of sagittal-view summary variables: Trunk angle (TA), pelvic tilt angle (PTA), and knee angle (B); hip angle (HA) and body position (BP) (C); pelvic position (PP) (D).

The warm-up was designed to provide time for power output and pedaling cadence to stabilize. Next, 10 seconds of video was recorded during the first 30-45 seconds of the next minute. The cyclist then dismounted the ergometer for approximately two minutes while the ergometer was set for the next trial. The entire lab visit lasted 80-120 minutes with no reports of fatigue by the cyclists.

2.2 Frontal Area Measurements

Using procedures previously described and validated (27,28), a measure of FA was determined for all trials from both Projects just prior to the start of each submaximal cycling trial. Measures of FA were derived from digital photographs with the cyclists looking forward at the camera and the left pedal placed at a 90° crank angle and the right pedal back at 270°. A calibration frame of known size and highlighted with reflective markers was placed in the field of view exactly midway between markers M1 and M2. The resulting digital images were analyzed using image processing software freely available in the public domain (ImageJ v1.45;U National Institutes of Health, Bethesda, MD USA). Each image of FA was compared to that of the in-view calibration image and converted to an area measure in units of m^2.

2.3 Instrumentation

The modified Serotta ergometer was equipped with the following: Thomson Elite seat post (L.H. Thomson Inc., Macon, GA USA) that allowed for the adjustment of saddle height and the micro adjustment of saddle tilt angle; LOOK Cycles ErgoStem HSC (Veltec Sports Inc., Sand City, CA USA); Profile AirWing "bull-horn" handlebars with Profile Split-Second aerobars (Profile Design, LLC, Long Beach, CA USA); adjustable carbon fiber crank set with a length range of 160-190 mm (Murray 'Tour de Force' Cycle Technology, Velddrif, South Africa); CompuTrainer™ resistance unit (RacerMate Inc., Seattle, WA USA) for controlling external power output and monitoring pedal cadence; Powertap power meter (Saris Cycling Group, Madison, WI, USA) mounted in the hub of the rear wheel as a secondary monitor of external power output. A separate CompuTrainer™ stationary trainer was used for evaluating cyclists on their own time-trial bicycles.

The cycle ergometer testing included the use of two different commercially available saddles (Figure 3): Adamo ISM Gel (Tampa Bay Recreation LLC, Lutz, FL USA) and the Profile Tri-Stryke Ti (Profile Design, LLC, Long Beach, CA USA). These two saddles were chosen because of their difference in design and use by cyclists. The Profile saddle is characterized as having a relatively long top surface (29 cm) and has a padded nose for sitting while using aerobars. In contrast, the Adamo saddle is relatively short (24 cm) and actually has no nose, while both saddles have a center cut out. The length difference between the saddles represents an actual difference in fore-aft movement ability when riding. The center cut outs and nose design differences, in contrast, are intended to reduce perineal pressure (thus improving rider comfort) such that cyclists can more comfortably adopt a saddle nose riding position when using aerobars. Saddle tilt angle remained level (0°) for Project I and either level or negative tilt (-10°, -5°, 0°) for Project II, where a negative angle indicated that the saddle nose dropped below the horizontal. Saddle tilt angle was determined by placing an inclinometer with a long straight edge across the high points of the front and rear of each saddle.

2.4 Data Processing

Sagittal-view video was recorded using a 60 Hz digital camera (model TK-C1380; JVC, Long Beach, CA USA) for each trial. From each recording, five successive pedal cycles were digitized using Motus v8.2 software (Peak Performance Technologies, Englewood, CO, USA). The digitized data were then smoothed using a Butterworth forth-order recursive filter with a 25 Hz cut-off frequency. For every cyclist, each kinematic variable of interest was then summarized as a mean of all digitized values across all five pedal cycles for each trial evaluated.

2.5 Statistical Analyses

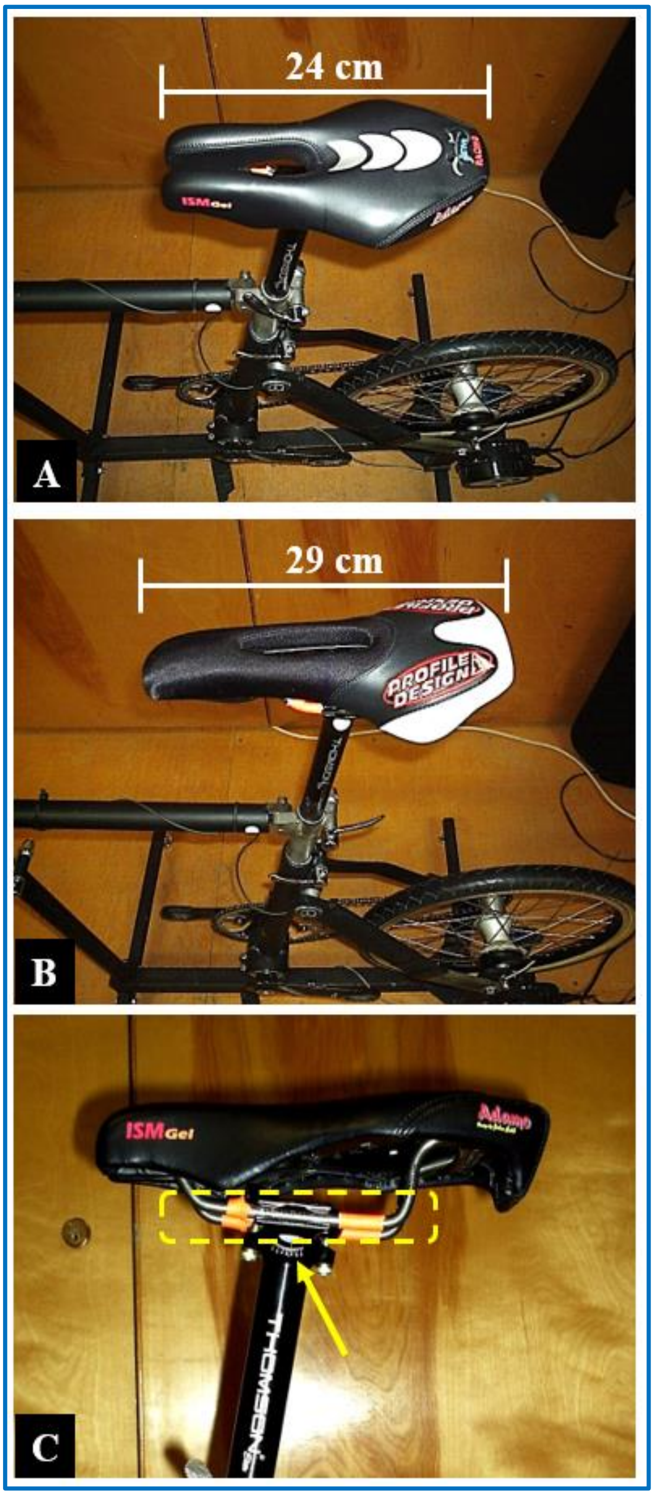

Figure 3. Photos of Adamo (A) and Profile (B) saddles used for Projects I and II testing. Also shown is how the Adamo saddle was centered on its rails (2C; within yellow dashed lines), as well as highlighting the micro adjustment scale on the seat post for controlling saddle tilt (2C; see yellow arrow).

The data from Projects I and II were evaluated separately since each Project tested different combinations of parameters. The outcomes for the video analyses for both Projects included mean values for each dependent variable of interest (HA, PTA, KA, BP, PP; Note that KA is only reported for Project II).

These variables were first evaluated using a multivariate repeated measures ANOVA to evaluate change as a function of each parameter tested in Project I or II (α = 0.05). Next, a combination of simple linear and multiple regression analyses was used to predict the performance markers (HA and FA) from a collection of independent variables (STA, TA, PTA, BP, PP) (α = 0.05). The emphasis of the regression analysis was on explaining variance in the performance markers (i.e., reporting R^2 only) rather than on generating prediction equations. All statistical analyses were performed using Statistix (v9.0; Analytical Software, Tallahassee, FL USA).

3 Results

3.1 Demographics

A total of eight men and two women cyclists were recruited for Projects I (Mean±SD: 36±9 years age; 76.9±8.5 kg body mass; 180.6±10 cm body height; 23.6±2.0 kg/m² BMI), while another five men and three women (36±9 years; 72.8±16.1 kg; 174.4±11.2 cm; 23.6±2.7 kg/m²) participated in Project II.

3.2 Kinematic Analyses

The primary outcomes for both Projects I and II were to describe how the cyclists' body kinematics changed in response to a wide range of bicycle geometry changes. A summary of these evaluations for Projects I and II are provided in Tables 2 and 3, respectively.

The Project I data analyses suggest that changes in TA was the most potent influence of change across the kinematic variables evaluated (Table 2). There was a mean difference of 18° between the "low" and "high" TA positions across all subjects and trials. This 18° increase was associated with significant increases in mean hip angle (+17°), pelvic tilt angle (+8°), BP (+14°), PP (+15°), as well as FA by an average of +0.035 m² (P<0.05). The change in STA from 76° to 80° was also associated with significant increases (P<0.05) in mean hip angle by +3°, BP by about 3°, PP by 4°, but not with pelvic tilt angle or FA.

Table 2. Summary of Project 1 kinematic variables, composite variables (body position and pelvic position), and frontal area calculations. All values expressed as Mean±SD units of degrees except for frontal area (m²), all values expressed in. Saddle sitting position (middle vs nose) was evaluated against type of saddle (Adamo vs. Profile), seat-tube angle (STA; 76° vs 80°), and trunk position ("low" vs "high"). Note that the the terms "Low" and "High" refer to the two trunk positions evaluated at each combination of seat-tube angle, saddle position, and type of saddle.

Saddle And STA	Saddle Sitting Position	*Trunk Angle		Hip Angle		Pelvic Tilt Angle		Body Position		Pelvic Position		Frontal Area (m²)	
		Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Adamo At 76°	Middle	6±5	24±3	59±4	75±5	53±9	60±7	105±6	119±3	85±5	99±3	0.34±0.03	0.36±0.03
	Nose	7±5	26±4	60±4	79±5	53±9	60±7	108±6	123±4	86±5	102±3	0.34±0.03	0.38±0.03
Profile At 76°	Middle	6±5	24±3	58±5	74±5	53±8	61±7	104±6	118±3	84±5	98±4	0.35±0.03	0.38±0.03
	Nose	7±5	26±4	61±5	78±5	53±8	62±8	108±7	123±4	87±5	102±4	0.35±0.03	0.38±0.03
Adamo At 80°	Middle	6±5	25±3	62±5	79±6	51±6	59±6	108±6	122±3	86±4	101±3	0.34±0.03	0.38±0.03
	Nose	8±5	26±4	65±5	82±5	51±6	59±6	112±5	126±4	89±4	104±3	0.35±0.03	0.39±0.03
Profile At 80°	Middle	8±8	24±4	63±9	78±6	50±7	60±6	108±8	122±4	87±7	101±4	0.35±0.03	0.38±0.03
	Nose	8±3	26±4	63±5	80±5	52±6	60±7	111±6	124±5	89±5	104±4	0.35±0.03	0.39±0.03

Moving from the middle to the nose of the Adamo and Profile saddles was associated with inconsistent changes in mean hip angle (0° to +3°), as well as no significant changes in pelvic tilt angle and FA, but consistent and significant increases in both BP and PP (+3° to 4°) ($P<0.05$). There did not appear to be any systematic differences in kinematic changes between the two brands of saddles tested.

The focus of Project II (Table 3) on the influence of saddle tilt angle found that as saddle tilt went from level (0°) to -10°, mean hip angle tended to increase by about 1° per -5° of tilt (significance between 0° and -10° only; $P<0.05$). Interestingly, pelvic tilt angle tended to decrease non-significantly as saddle tilt became more negative, but both BP and PP increased consistently and significantly between saddle tilts of 0° and -10° by 2-4°. Table 3 also shows that mean knee angle tended to decrease significantly with movement from the middle to the nose of the saddle (-2° to -5°; $P<0.05$), as well as when saddle tilt became more negative (-2° across all trials; $P<0.05$). While not reported in Table 2 for Project I, the influence on saddle sitting position (middle versus the nose) on mean knee angle was similar as that described for Project II (Table 3). Finally, saddle tilt angle had no significant influence on changes in FA.

3.3 Regression Analyses

The regression analyses focused on the ability to explain variance in either mean HA, an indicator of metabolic power production, or FA, a determinant of aerodynamic drag. Using standard step-forward regression procedures with the data from Project I, a combination of three variables (STA, TA, saddle sitting position) explained 85% of the variance in HA, while either BP or PP alone explained 68% and 79% of the variance, respectively. To explain changes in FA, however, single variable models that included TA, BP, or PP were used to explain 80%, 83%, and 84% of the variance. Other combinations of variables were not possible due to non-significance or violations of covariance (e.g., BP, PP, and pelvic tilt could be included in the same regression models). For Project II, the combination of STA, TA, pelvic tilt, and saddle sitting position explained 84% of the variability in According to Olds et al. (2), time-trial cycling can be accurately modelled as a balance between factors that contribute to the "power supply" of the cyclists versus external factors that contribute to "power demand". Based upon the results of previous studies (9-11), changes in mean HA could be considered a marker of "power supply", likely because changes in HA infers that changes in muscle-tendon mean HA while either BP or PP variables alone explained 65% and 78%, respectively. Finally, a model including STA, TA, and saddle sitting position explained only 75% of the variability in FA ($P>0.05$), while BP explained 80% and PP explained 83% of the variability ($P<0.05$).

4 Discussions

The primary goal of this study was to describe the sagittal-view kinematics of cyclists who experienced the systematic variation of multiple bicycle geometry variables in a controlled lab setting. In addition, this study also sought to determine how sensitive two markers of cycling performance (FA and mean HA) were to changes in both geometry and kinematic variables in this study. There were several trends to emerge from both Projects I and II.

Length (and thus muscle function) must also be occurring (29). For the current study, there were three geometry variables from Project I (TA, STA, saddle sitting position) and another four from Project II (STA, TA, saddle sitting position, saddle tilt angle) that explained either 85% or 84% of the changes in mean HA. This suggests that any factor influencing how and where the cyclist's body contacts the saddle can potentially influence mean HA and thus "power supply" either positively or negatively.

This may be the first report to document how both saddle tilt angle and saddle sitting position can influence a kinematic marker of "power supply" in cyclist In practice, measures of TA and STA are generally configured by cyclists and bike fit specialist to a combination that minimizes aerodynamic drag while also allowing for enough comfort to maintain an aerodynamic position. Saddle tilt angle and sitting position are then used as secondary modifiers of bicycle fit to the primary parameters of TA and STA. For example, many time-trial cyclists adopt a saddle nose riding position and/or to drop the saddle tilt angle to provide more comfort when riding in an aerodynamic position. The current study results suggest that these secondary modifiers of bicycle fit may also influence the power producing ability of the hip extensor muscles.

Table 3. Summary of Project 2 kinematic variables, composite variables (body position and pelvic position), and frontal area calculations. All values expressed as Mean±SD units of degrees except for frontal area (m^2). Saddle angle (SA) condition values were evaluated at combination of saddle type (Adamo vs Profile), seat-tube angle (STA; 76° vs 80°), and saddle sitting position (middle vs nose) while trunk angle was held constant.

Saddle and STA	SA	Hip Angle		Pelvic Tilt Angle		Knee Angle		Body Position		Pelvic Position		Frontal Area (m^2)	
		Middle	Nose	Middle	Nose	Middle	Nose	Middle	Nose	Middle	Nose	Middle	Nose
Adamo At 76°	0°	52.5±7.8	55.7±8.5	59.6±7.8	58.4±8.4	107.1 ±6.3	104.8 ±6.7	99.7 ±5.3	104.7 ±4.6	82.0±5.5	85.5±5.4	0.31±0.03	0.32±0.03
	-5°	53.1±8.2	56.1±8.5	59.0±8.4	58.8±8.4	104.4 ±8.4	103.5 ±6.8	101.0 ±8.4	105.8 ±6.8	83.1±5.5	86.4±5.3	0.31±0.03	0.32±0.03
	-10°	53.9±9.3	56.5±8.1	58.1±10	58.5±10	105.4 ±5.7	102.2 ±6.5	102.1 ±7.1	107.0 ±4.8	84.2±6.8	87.6±5.1	0.32±0.03	0.33±0.03
Profile At 76°	0°	52.3±8.4	54.7±9.0	60.7±11	61.0±10	107.0 ±5.6	104.8 ±5.2	99.8 ±5.3	104.5 ±5.9	82.2±5.5	85.3±5.8	0.30±0.03	0.31±0.03
	-5°	52.4±8.0	55.4±8.3	60.1±11	61.1±11	106.1 ±5.8	102.7 ±6.2	100.4 ±5.3	106.2 ±4.5	82.5±5.5	86.6±5.2	0.30±0.03	0.32±0.03
	-10°	53.0±8.5	56.4±9.2	58.8±10	59.5±11	105.1 ±4.4	101.2 ±5.9	101.2 ±5.4	107.3 ±4.9	83.4±5.9	88.0±5.7	0.31±0.02	0.32±0.02
Adamo At 80°	0°	56.6±9.0	58.5±9.3	56.1±10	56.2±11	108.2 ±7.0	105.8 ±9.0	104.1 ±7.0	108.3 ±7.4	85.4±6.4	88.1±6.7	0.30±0.02	0.31±0.03
	-5°	57.0±8.8	59.2±10	55.6±9.7	56.6±11	107.4 ±6.6	105.1 ±7.9	104.9 ±5.9	108.9 ±6.5	85.7±5.9	88.6±6.5	0.30±0.03	0.32±0.03
	-10°	57.9±9.5	60.0±9.4	54.1±9.7	55.9±10	106.5 ±7.0	103.5 ±7.3	105.8 ±7.2	111.2 ±5.3	86.6±6.6	90.0±6.0	0.31±0.03	0.33±0.02
Profile At 80°	0°	53.9±8.4	57.0±8.1	59.4±9.1	59.9±9.8	107.4 ±5.8	105.1 ±6.0	102.1 ±4.8	107.3 ±3.6	84.0±5.2	87.6±4.6	0.31±0.03	0.31±0.02
	-5°	52.2±14	58.5±8.8	57.9±9.4	58.8±10	106.6 ±5.6	103.8 ±6.0	103.2 ±5.2	108.9 ±4.2	84.9±5.8	88.7±5.2	0.30±0.03	0.32±0.02
	-10°	56.4±8.7	59.4±8.7	56.4±10	57.8±11	107.0 ±7.0	103.4 ±7.4	104.5 ±5.3	110.2 ±4.1	85.5±5.6	89.5±5.3	0.30±0.03	0.30±0.03

Interestingly, the measure of pelvic tilt angle did not contribute significantly to the explanation of HA variance for either Project I or II. However, this may be due to difficultly with tracking and digitizing the ASIS marker accurately (M4 in Figure 2A) when cycling in an aerodynamic position. This statement is supported by the observation that the composite angle of PP, which includes the PSIS marker (M3 in Figure 2A) and not the ASIS marker, explained more variance in HA than any other single geometry or kinematic variable for either Project I or II. The idea behind creating the PP composite angle was that its measure could theoretically account for changes in TA, HA, STA, saddle sitting position, or saddle tilt angle. In fact, as a predictor of HA, the PP composite angle consistently explained more variance in HA than BP. As the other composite angle evaluated in this study, BP was envisioned to be sensitive to the same types of changes as described for PP (i.e., changes in TA, HA, STA, saddle sitting position, or saddle tilt angle), except that its measure was anchored to the greater trochanter marker (M5 in Figure 2A) rather than the PSIS marker. As such, it was thought a priori that BP would be less sensitive to changes in HA if, in fact, pelvic tilt angle changes were important to describing changes in HA. Indeed, PP consistently explained more variance in HA (78-79%) than BP (65-68%) across both projects.

A unique characteristic of this study is how the variety of geometry and kinematic changes were related to changes in frontal area (FA). Using one or more geometry variables, 75-80% of the variability in FA could be explained from both projects. In contrast, using just the composite angles of BP (80-83%) or PP (83-84%) explained as much or more variance in FA than was possible with the geometry variables. Clearly, the composite angles are doing a better job at describing how the body of the cyclist is projected in the frontal plane than any combination of geometry variables evaluated.

Finally, there are several other observations from this study worth noting. First, the observations noted above all seem to be independent of the two types of saddles tested. Thus, despite drastic difference in appearance between the two saddles (Figure 3), it is more likely that rider comfort on the saddle has more to do with the choice of saddle by cyclists than any other factor. Another interesting observation was that mean knee angle (KA) tended to decrease as cyclists moved from the middle to the nose position of the saddle, as well as tilting the saddle from 0° to -10° (Table 3). It is well documented that KA movement patterns will remain constant (±1°) even with quite drastic changes in STA and TA (10). The present study, however, documented systematic decreases in KA by 2-4° which is a similar kinematic outcome to decreasing saddle height (3). Thus, while adjusting saddle tilt angle and saddle sitting position may be attempted to alleviate riding comfort, lower-limb power production may be comprised with subsequent changes in HA and/or pelvic tilt angles, as well as KA.

4.1 Study Limitations

There are several limitations to this study worth noting. First, the duration of cycling for each condition for both Project I and II were only a few mins in duration. This measurement strategy was adopted to minimize the amount of time for each lab visit and to minimize the influence of fatigue. As such, it is possible that lower limb kinematics will change as the cyclist fatigues, though no such observations have been reported in the research literature. Regardless, the present study findings should be considered as delimited to non-fatigued steady-state cycle ergometry. Second, it is likely that body kinematics of the cyclist are considerably different than riding outdoors or within an actual time-trial race than in a lab on a stationary ergometer. Thus, again, the present study finding should be considered delimited to stationary cycle ergometry.

4.2 Practical Applications

This study has demonstrated that the complex interaction of fitting a cyclist to a bicycle can be summarized by the pelvic position (PP) composite kinematic variable better (i.e., explain more variance in changes in hip angle) than any other single sagittal-view kinematic variable evaluated by this study. As a composite angle, PP appeared to be sensitive to changes in a variety of bicycle geometry variables (trunk angle, seat tube angle, saddle sitting position, and saddle tilt angle) as well as kinematic variables (hip angle, pelvis tilt angle). In addition, differences in PP also explained more variance in frontal area, a determinant of aerodynamic drag, than any other combination of geometry or kinematic variables assessed by this study. Thus, this single composite angle that integrates traditional body kinematics with the bicycle itself can explain the majority of variance in factors related to both physiological power production (i.e., changes in hip angle) and minimizing aerodynamic drag (i.e., changes in frontal area). In addition, this study has shown that both saddle sitting position and saddle tilt angle have the potential to influence body kinematics, while many other researchers have linked changes in kinematics to changes in oxygen uptake and power production. Obviously, this study is limited to the fact that the entire study was completed under laboratory-controlled conditions. With that limitation in mind, the present study can still be used as a reasonable starting point for understanding the interaction of bicycle geometry and body kinematics to dictate factors related to the generation of physiological power and the minimization of aerodynamic drag for time-trial cycling.

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