Uphill Cycling: Investigating the Effects of Saddle Incline on Comfort, Frontal Area, and Power Output

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Abstract
This study investigates the impact of saddle inclination on cycling comfort, frontal area, and power output during uphill cycling, a key challenge in events like the Tour de France. While bike-fitting and bicycle geometry advances have enhanced the cycling experience, little research has focused on bike-fitting for uphill cycling and optimizing saddle tilt for uphill performance. Recently, the adoption of saddle incline by top cyclists such as Tadej Pogačar and 2016 amendments to the Union Cycliste Internationale's (UCI) regulations have increased interest in the benefits of saddle incline. Previous studies have suggested the following benefits from saddle incline: 1) increased comfort [6], 2) improved metabolic power efficiency [4], 3) positively modified muscle activation [2, 4, 7], 4) decreased perceived exertion [7], and 5) reduced oxygen consumption [5]. All of those could improve performance on challenging climbs. To further assess the precise biomechanics and potential benefits of saddle incline, this study will examine 1) comfort, 2) projected drag area, and 3) power output. Thirteen cyclists of varying experience levels participated in four sessions with saddle inclinations of 0°, 2°, 4°, and 6° while cycling on a simulator set to a 4° uphill slope. The results of this study indicate that there is no definitive ratio between saddle inclination and slope angle that universally optimizes comfort, aero, and power output for all riders. Notably, the saddle incline-to-slope ratio does influence comfort but is highly individualized. A 4° saddle incline received a mean comfort score of 7.4 ± 1.5, while a 0° saddle incline scored a lower 6.76 ± 1.74. The projected frontal area, a key measure in aerodynamics, was 1.5% lower when comparing a 4° inclined saddle to a horizontal saddle but was not statistically significant. Power output was greater for a horizontal saddle, with a measured 1,02% increase in power output compared to the lowest score gathered from a 4° saddle incline. However, this result was also not statistically significant.

Keywords: Uphill cycling, Saddle incline, Frontal area, Power output, comfort, Biomechanical efficiency.

1. Introduction
In recent decades, cycling has seen significant advances in the understanding and application of biomechanical principles, leading to enhanced performance and safety for both competitive and recreational cyclists. Bike-fitting professionals, manufacturers, and researchers have all investigated the effects of various bicycle parameters on cycling comfort, performance, aerodynamics, and overall cycling experience. This surge in knowledge has spurred the investigation of bicycle geometry parameters, such as but not limited to 1) saddle height, 2) saddle fore-aft position, 3) saddle angle, 4) seat-tube angle, 5) handlebar height, 6) saddle-to-stem distance, 7) handlebar width, 8) stem length, 9) stem angle, 10) cleat positioning, 11) crank arm length, 12) foot-pedal interference, and 13) Q-factor adjustments [1].

Nevertheless, the specific impact of these parameters on uphill cycling—a critical aspect of winning races like the Tour de France—has received relatively little attention. Uphill cycling presents unique challenges such as 1) increased resistance, as gravity acts against the cyclist's forward motion; 2) shifts in body position, as gravity pulls the cyclist's body backward and off the saddle; 3) Altered pedal force application changes the angle at which cyclists push the pedals relative to the ground; 4) increased muscle activation from the hamstrings, glutes, lower back, arms, and shoulders to counteract the backward pull and maintain position; and 5) changes in saddle weight distribution [2].

There has been a recent increase in awareness for saddle inclination due to a 2016 Union Cycliste Internationale (UCI) regulation change, which permits a saddle tilt of up to 9°, with a 1° margin of error [3]. This is underlined by elite cyclists', such as Tadej Pogačar's adoption of a slightly downward-facing saddle for uphill races, underscoring potential benefits at the highest competitive levels.

The conventional belief is that tilting the saddle downward on a slope allows cyclists to leverage the friction force between their body and the saddle to counteract the pull-back force of gravity. The counteracting force would be metabolically free relative to heavy muscular compensation on the pedals and handlebar to maintain seating position. One study showed that tilting the saddle nose down by 8°

when cycling up an 8° slope improved gross metabolic efficiency by 1.4% ± 0.2% [4]—suggesting that a 1:1 saddle incline to slope ratio would provide a 1,4% improved metabolic efficiency. However, the metabolic effect for other saddle-to-incline ratios or for higher to lower uphill slopes remains unknown and would likely vary. Another study reported reduced elbow-flexor activity resulting in a shift towards free metabolic saddle friction. Wilkinson suggested this could account for the 1,4% overall reduction in metabolic power [4, 5].

When looking at the effect of saddle incline on comfort, Hynd et al.'s 2018 study indicates that a level saddle on a 15% or 30% uphill slope is less comfortable than a 5° downward saddle incline at a 15% (8.5°) uphill slope or a 10° downward saddle incline at a 30% (16.7°) uphill slope [6]. Alternatively, it could be stated that a saddle incline-to-slope ratio of 0,59:1 offers higher comfort compared to a horizontal saddle position. For example, a 4° slope would correspond to a 2.37° saddle incline – if the ratio would be characterized as perfectly linear, which remain uncertain and rather unlikely.

Ultimately the goal of saddle inclination is to optimize for all proposed benefits, e.g., 1) increased comfort [6], 2) improved metabolic power efficiency [4], 3) positively modified muscle activation [2, 4, 7], 4) decreased perceived exertion [7], and 5) reduced oxygen consumption [5], - all of which could improve performance on challenging climbs.

Toward that goal, this study will assess the effect of saddle incline on 1) comfort, 2) projected drag area, and 3) power output with three null hypotheses: a) There is no significant effect of saddle inclines of 0°, 2°, 4°, and 6° on cycling comfort during a 4° uphill slope, b) There is no significant effect of saddle inclines of 0°, 2°, 4°, and 6° on the projected frontal area for a 4° uphill slope, and c) There is no significant effect of varying saddle inclines of 0°, 2°, 4°, and 6° on power output during a 4° uphill slope.

2. Methodology

Thirteen cyclists (12 males, one female) participated in the study, with a mean age of 25.7 ± 2.7 years, a mean height of 179.8 ± 9.2 cm, and a mean body mass of 73.7 ± 9.8 kg. Participants were categorized into four levels based on their weekly cycling activity: one cyclist was classified as advanced (≥ 200 km/week), five as intermediate (100–200 km/week), three as novice (50–100 km/week), and four as recreational (± 50 km/week).

Each participant completed four sessions with saddle inclines adjusted to 0°, 2°, 4°, and 6°, relative to the horizontal ground plane, as shown below in figure 1. These inclines were within the allowable limits set by the UCI [3]. The order of the sessions was rotated among participants to control fatigue effects. The first participant completed the sessions in the following order: 0°, 2°, 4°, and 6°, while the second participant started with a saddle incline of 6°, and so on. In addition, participants were allowed to rest for 5 minutes between each session. Saddle inclination was measured and adjusted using a digital angle protractor (Neoteck, Levelbox).

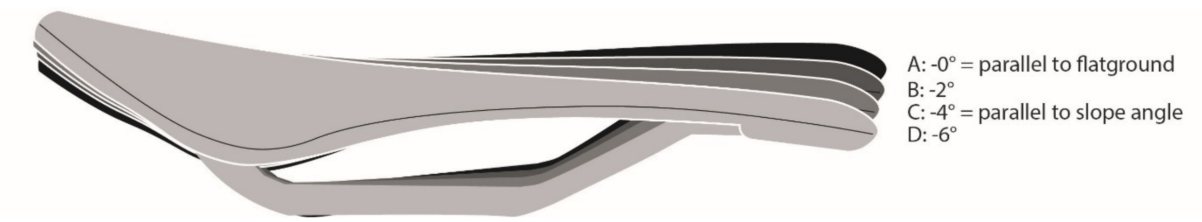

Fig. 2. Four saddle position inclines tested on a 4° slope.

Participants began with a 5-minute warm-up to reach and stabilize around their estimated third heart rate zone according to the Fox and Haskell formula [8, 9], to control exercise exertion across all four sessions [10]. Data on frontal area, heart rate, wattage, and comfort were collected during the final 5 minutes of each 10-minute session.

The sessions were performed using participants' own road bikes mounted on an aerodynamic cycling simulator named FAAST, shown in Figure 2 below [11]. The simulator was placed on a motorized platform set to a 4° uphill slope (equivalent to 8%).

FAAST can monitor the real-time projected frontal area of the rider and bicycle with a reliability of ±1%. The camera's reliability was determined through repeated measurements of a surface with a known frontal area. This camera continuously captures the rider's frontal profile. Once the frontal area is determined, the following aerodynamic drag equation to calculate the drag force (Fd) acting on the rider is used:

$$Fd = \frac{1}{2} \times \rho \times v^2 \times Cd \times A + additional\ terms \qquad (1)$$

Where:

- ρ is the air density $\left[\frac{kg}{m^3}\right]$
- v the velocity of the cyclist, relative to the velocity of the wind $[\frac{m}{s}]$
- Cd is the drag coefficient $[-]$
- A is the frontal area calculated by the depth camera $[m^2]$
- Additional terms: rolling resistance & resistance from bearings

The calculated drag force is fed into a feedback loop with the Wahoo KICKR V6 smart trainer (Wahoo, USA) [13]. As the projected frontal area increases or decreases based on the rider's posture, the Wahoo KICKR V6 adjusts the cycling resistance, simulating the effect of aerodynamic drag forces. In addition, based on weight and the set slope, the smart trainer's resistance is increased to simulate the gravitational effect on an uphill incline using the following formula:

$$Fg = m \times g \times \sin \alpha$$

Where:

- m is the mass of the cyclist and his bicycle $[kg]$
- g is the gravitational constant $[N/kg]$
- α is the uphill incline [°]

Power measurements were collected from the Wahoo KICKR V6 smart trainer, which provides power measurements (wattage) with an accuracy of ± 1.1% for outputs ranging from 200 W to 750 W [14]. Lastly, heart rate was captured using a Polar H10 (Polar, Finland) chest strap [15]. The average heart rate of each participant for each of the four sessions was compared to control for variations in exertion levels, which could significantly influence power output measurements.

Fig. 2. Experiment setup using FAAST on an uphill gradient of 4°. The image to the left shows a researcher using the FAAST system to perform the pilot experiment. The image to the right shows the saddle at a 9° incline.

Comfort scores were measured using a Likert scale, with participants asked to rate their comfort and provide feedback after each session. Participants were asked: 1) How would you rate your overall comfort on a scale from 1 to 10 during this session? 2) Did you feel any general discomfort during this ride? If yes, where did you feel it? 3) Did you experience pain or discomfort in your lower back, hips, or upper body? 4) During pedaling, was there any discomfort in your legs (thighs, knees, or calves) or feet? 5) Did you notice increased pressure or pain in the sit bones or pelvic region? 6) Did your arms, shoulders, or hands feel strain or discomfort during the session? After completion of all four sessions, participants were allowed to adjust their scores and offer additional input.

3. Results

3.1. Comfort

On average, all three tilted saddle inclines performed better than a saddle in a horizontal position. However, the null hypothesis is adopted—a non-parametric Friedman test comparing all four saddle positions indicated no significant increase in comfort ($p = 0.246$, $p > 0.05$) on a 4° slope. This suggests that saddle inclines do not significantly enhance rider comfort under these conditions, and thus, the results below should be interpreted with caution.
As shown in Table 1 below, a saddle incline of 4° performed best with a mean comfort score of 7.4 ± 1.5, while a 0° saddle incline performed worse with a mean comfort score of 6.76 ± 1.74. Tilting the saddle nose from 0° to 4° improved the gross comfort score by 9.09% ± 2.25%.,

Table 1. Descriptive statistics comparing comfort scores between saddle inclination angles of: 0°, 2°, 4°, and 6° on a 4° slope.

Saddle incline session	N	Mean comfort score	Std. Deviation	Minimum	Maximum
0°	13	6,8	1,7	3,0	9,0
2°	13	7,1	1,7	4,0	9,0
4°	13	7,4	1,5	4,0	9,0
6°	13	7,2	1,1	6,0	9,0

Comfort scores from this observation suggest that for a 4° slope, the optimal saddle incline-to-slope ratio lies between 0.5:1 to 1.5:1 and that a 1:1 ratio tends to score highest in comfort for most individuals. These results suggest no definitive ratio between saddle inclination and slope angle when optimized for comfort. Like other bike-fitting parameters, it should be tailored to the rider's needs.

3.2. Frontal Area

The average frontal areas across the saddle inclines of 0°, 2°, 4°, and 6° were 0.333 m², 0.330 m², 0.328 m², and 0.333 m², respectively. Despite the lack of statistical significance, a 1.5% decrease in frontal area was observed between the 0° and 4° saddle incline.
However, using repeated measures ANOVA with $(\alpha = 0.05)$, this was found to be not statistically significant. Therefore, our second null hypothesis is adopted: there is no significant effect of varying saddle inclination (0°, 2°, 4°, 6°) on the projected frontal area for a 4° uphill slope.

Table 2. Descriptive statistics comparing average area (m^2) between saddle inclination angles of 0°, 2°, 4°, and 6° on a 4° slope.

	N	Mean frontal area (m^2)	Std. Deviation
0°	13	0.333	0.035
2°	13	0.330	0.036
4°	13	0.328	0.035
6°	13	0.333	0.032

3.3. Power Output

Descriptive statistics on power output are provided in table 3, which include all thirteen participants. Table 4 excludes the four recreational riders (+-50 km/week) due to a potentially greater influence of fatigue on their power output in later sessions. In addition, power output of the Wahoo KICKR V6 is less accurate at lower wattages which could contribute to measurement inaccuracies from the recreational riders.

On average, the horizontal saddle position had the highest power output across both analyses; however, it was not statistically significant. Notably, power output was lower in the 2° and 4° sessions, which is likely attributed to their placement as the second or third session. In the future, all sessions should be rotated to start first. However, you could cautiously state that the differences in power output are still not great enough to indicate that there is a difference in biomechanical efficiency for saddling inclines of 0, 2, 4, and 6 degrees in a 4° slope. In fact, after controlling heart rate exertion, no significant effect on power output was measured ($\alpha = 0.05$). Therefore, our null hypothesis is not rejected: there is no significant effect of saddle inclines of 0°, 2°, 4°, and 6° on power output during a 4° uphill slope.

Table 3. Descriptive statistics for all thirteen-participant comparing power output (W) between saddle inclination angles of 0°, 2°, 4°, and 6° on a 4° slope.

Saddle incline session	N	Mean power output (W)	5% trimmed mean power output (W)	Std. Deviation	Minimum	Maximum
0°	13	197,51	200,81	47,30	78,50	257,00
2°	13	193,05	195,83	48,70	76,10	260,10
4°	13	192,82	195,23	50,61	73,40	268,90
6°	13	193,75	195,78	50,05	77,30	273,90

Table 4. Descriptive statistics for nine participants (excluding recreational riders) comparing power output (W) between saddle inclination angles of 0°, 2°, 4°, and 6° on a 4° slope.

Saddle incline session	N	Mean power output (W)	5% trimmed mean power output (W)	Std. Deviation	Minimum	Maximum
0°	9	210,30	209,53	30,38	177,30	257,00
2°	9	209,70	208,91	32,91	173,5	260,10
4°	9	208,17	207,14	36,63	165,90	268,90
6°	9	210,20	209,23	37,16	163,90	273,90

3.4. Interview results

3.4.1. Results from advanced and intermediate cyclists only

When analyzing these results, it is apparent that while most participants preferred an inclined saddle, it resulted in an overall increase in discomfort in the gluteal region. This is likely a result of the increased contact force between the body and the saddle. This force is metabolically free and could be a reason participants felt like they had an increase in power efficiency, as they require less upper body or pedal force compensation to remain seated. Notably, power measurement shows no increase in power output for the inclined saddle positions, which does not fall in line with feedback from the participants.

Table 5. Summary of likes, dislikes, and neutral scores with their main influencing factors, based on opinions gathered from interviews with advanced and intermediate participants (400 km/week and 200 km/week).

Saddle incline	Liked (# participant)	Disliked (# participant)	Neutral (# participant)	Main reasons for liking	Main reasons for disliking
0°	1	3	1	1) most common saddle position, “felt normal”	1) arm pain, 2) discomfort due to sliding backward and 3) pressure on arms
2°	3	1	1	1) “smoother” pedaling, 2) improved weight distribution, and 3) overall comfort	1) increased pressure on sit bone, causing discomfort, 2) arm pain, and 3) repositioning
4°	3	1	1	1) “smoother” pedaling, 2) improved weight distribution, and 3) overall comfort	1) lower back pain 2) increased pressure on sit bone, causing discomfort, 3) repositioning, and 4) felt like hanging backward
6°	1	2	2	1) improved weight distribution, 2) improved power transfer, and 3) reduced reliance on upper body for support.	1) Discomfort due to forward weight shift and pressure on arms and knees, and 2) felt like hanging backward

3.4.2. Horizontal saddle inclination (0°)

In sections 3.4.2 – 3.4.5, interview results from all thirteen participants are gathered. However, these include riders with less experience, and therefore results should be considered more cautiously.
When considering all participants, the 0° incline garnered mixed reviews. Many participants found it comfortable, due to it being the setting most riders are accustomed to. One rider stated that it allowed for maintaining a good cadence. Two riders reported discomfort in the groin area due to the saddle's nose. Two participants experienced arm pain that persisted throughout the test, while another felt that the saddle pressure was uneven and made it difficult to maintain a stable position, as they frequently slid backward.

3.4.3. Saddle inclination (2°)

The 2° incline produced a range of reactions. Riders often did not feel a significant difference compared to the horizontal position, the most common report being arm pain. Riders who appreciated the incline mentioned better pedal force application and an overall improved performance. Two riders expressed discomfort, specifically too much pressure on the arms and sitting bones. For larger cyclists with a more forward-shifted center of gravity, the slight incline may cause them to slide forward off the saddle, forcing them to compensate with their arms. Conversely, other participants reported needing to frequently reposition themselves due to sliding backward.

3.4.4. Saddle inclination (4°)

At 4°, the feedback was again divided. Many riders appreciated the incline particularly in terms of better power transfer and seating position. One rider reported better weight distribution on the saddle, which helped with smoother pedaling. However, some participants found the incline uncomfortable due to excessive pressure on their sit bones. Riders also noted discomfort in the lower back and pelvis, making it harder to maintain a comfortable riding position.

3.4.5. Saddle inclination (6°)

The 6° incline received either strong negative or positive feedback, with several riders noting an improved ability to maintain higher wattage. One rider highlighted reduced reliance on the upper body for support. Contradictorily, other riders found the incline too steep, experiencing discomfort in their arms and knees due to their weight shifting too far forward.

4. Discussion

This study aimed to investigate the impact of saddle inclination on cycling comfort, aerodynamic drag, and power efficiency on a 4° uphill slope.

The highest mean comfort score was attributed to the 4° saddle incline with a mean score of 7.4 ± 1.5, while the 0° saddle incline scored a lower 6.76 ± 1.74. These results suggest that, in general, inclined saddles outperform a horizontal saddle position regarding comfort, although this difference was not statistically significant. Interestingly, the minimum and maximum comfort scores for all sessions indicate that there is an impact on perceived comfort but that its impact is highly individualized. For example, it was noted that larger cyclists with a more forward-shifted center of gravity tend to slide forward off the saddle, requiring them to compensate with their arms. As a result of the forward shifted center of gravity, larger cyclists may only benefit from a smaller saddle incline-to-slope ratio, while smaller cyclists might be more suited to a higher saddle incline-to-slope ratio.

Although an optimal saddle incline-to-slope ratio for comfort could not be precisely defined, ratios of 0.5:1 and 1.5:1 showed potential for riders who do enjoy an inclined saddle. These findings should be considered as guidelines rather than a fixed rule when optimizing for comfort due to the nonstatistical significance of these results.

Results for the frontal area indicated a 1.5% reduction in the mean frontal projected area between the 0° and 4° inclined saddle positions, although this change was also not statistically significant. They indicate that a 1:1 saddle incline-to-slope ratio is optimal, however, with only a very marginal difference.

Power output was greater for a horizontal saddle, with a measured 1,02% increase in power output compared to the lowest score gathered from a 4° saddle incline. However, this result was also not statistically significant.

5. Future Works

Notably, the aerodynamics of the cyclist could also be influenced by saddle inclination through changes in the rider's posture and body shape due to saddle incline. Even if the total frontal area remains mostly unchanged, subtle adjustments in saddle incline could alter the rider's profile, potentially affecting airflow and creating areas of drag. Future studies could use wind tunnel or CFD simulations (Computational Fluid Dynamics) to analyze aerodynamic flow around the body due to changes in posture.

Furthermore, to understand the precise biomechanics of saddle inclination on cyclist's biomechanics all three contact points and the center of gravity should be measured: 1) saddle, 2) pedal, and 3) handlebar forces 4) center of gravity. Special attention should be given to handlebar forces, which have been underexplored, to assess further how upper extremity muscle compensation affects the overall cycling experience.

Lastly, it is likely that saddle inclination has an increased effect on steeper slopes due to the increase in gravitational force acting to pull the rider off the saddle. Future studies should investigate the impact on steeper slopes, such as 20%, to highlight the effects of varying saddle inclines. Additionally, expanding the range of saddle inclinations up to 9° per UCI allowed standard. Including decline settings could help understand their influence on comfort and performance.

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