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Journal of Science & Cycling
Breakthroughs in Cycling & Triathlon Sciences

Original Article

Practical Insights into Crank Arm Length Selection: Effects on Cycling Performance and Metrics in an Augmented Reality Environment

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Received: 1 December 2025 **Accepted:** 21 March 2026 **Published:** 27 March 2026

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Abstract

The purpose of this study was to identify whether cycling time trial (TT) performance and cycling metrics are affected by small changes in crank arm length (CAL). Fourteen subjects (8 male; 6 female) completed three cycling TTs with different CALs (i.e., 165, 170, and 175 mm) on three separate occasions along a designated virtual course (distance: 11.65 km, elevation: 34.1 m) using a smart bike integrated with augmented reality (AR) software. A repeated measures ANOVA was conducted to analyze the effect of CAL on various cycling metrics: cadence (rpm), pace ($m \cdot s^{-1}$), power ($W \cdot kg^{-1}$), TT performance (min), energy expenditure (kJ), heart rate (bpm), and rate of perceived exertion (RPE), with appropriate *post hoc* tests as needed. Cadence, pace, and TT performance showed significant main effects across CALs ($p < 0.05$). However, no statistical differences were observed in cycling power, energy expenditure, average heart rate, or RPE ($p > 0.05$). Smallest worthwhile change (SWC) analysis revealed that performance differences between 165 and 170 mm may still hold practical significance despite statistically non-significant post hoc comparisons ($p > 0.05$). These findings suggest that a shorter CAL is associated with faster completion time under controlled conditions due to higher cadence and faster pace without increasing physiological strain. Practically, recreational cyclists and novice triathletes may consider slightly shorter crank arms to improve short-to-moderate distance cycling performance. In addition, an augmented reality platform combined with a smart bike provides a reproducible and ecologically valid method for training and applied performance assessment.

Keywords

endurance cycling; virtual cycling environment; smallest worthwhile change

1 Introduction

Cycling performance interacts with various physiological (3,7,8,19,20), biomechanical (1,10,27,28,29,30) and other parameters such as muscle activities (12,21). When it comes to the characteristics of cycling, bike fit including saddle height, seat tube angle, handlebar reach, crank arm length affects many aspects of cycling metrics such as physiological responses, joint kinematics, kinetics, muscle activation, and the likelihood of overuse injuries during endurance cycling (14,23,25). Among those bike fit variables, crank arm length (CAL) has recently drawn attention in both the sport science research and the cycling community (16,21,24). For these reasons, numerous studies have investigated the effect of different CALs on cycling metrics and performance in order to identify the optimal CAL for maximizing cycling power output and performance.

Previous studies have been demonstrated that a CAL of approximately 165 mm produces greater peak and mean power output among various range of CALs from 125 to 225 mm (11). Similarly, a CAL of 180 mm has been shown to yield higher power output than 110, 145, 230, and 265 mm during a 30-s supramaximal anaerobic cycling test (28). Additionally, 145 and 170 mm CALs yielded the higher power outputs when compared to 120, 195, and 220 mm CALs during maximal inertial load cycling (17). Furthermore, this study demonstrated an inverse relationship between CAL and cadence, showing that longer CAL result in slower cadence (rpm), but higher pedal speed ($m \cdot s^{-1}$) to compensate for decreasing cadence and vice versa. In addition, a previous study examining joint-specific and maximum cycling power across five CALs (i.e., 150, 165, 170, 175, and 190 mm) found that CAL does not significantly affect joint power output (i.e., hip, knee, and ankle) or maximum cycling power (1). This resulted in the conclusion that competitive cyclists could choose any standard CALs (i.e., 165, 170, and 175 mm) based on factors such as reduced aerodynamic drag and risk of injury without the concern of compromising changes in relative joint angles and power output.

Even though previous studies have effectively demonstrated the relationship between CALs and various cycling metrics, several investigations have employed unrealistically wide ranges of CALs as well as relatively short duration which are hardly applicable to the real-world cycling (1,11,17,28,29). Notably, some studies have used a quite wide range of CALs (e.g., 110–265 mm) (28,29), whereas most cyclists typically choose commercially available "standard" CALs (i.e., 165, 170, and 175 mm) (1,8,15,16,21). This raises the question of whether small, more practical changes in CAL meaningfully affect cycling performance and related physiological and biomechanical parameters. A previous study has compared three commonly used CALs (170, 172.5, and 175 mm) across peak power, isokinetic cycling, and maximal tests; although performance and power output did not differ significantly, they suggested that 170 mm may offer practical advantages when cadence and power must vary with race tactics and terrain (16). Another study has examined submaximal pedalling mechanics using standard CALs (165, 170, and 175 mm) and non-standard CALs (150 and 190 mm) and reported significant differences in hip angular velocity and peak power primarily in comparisons involving the non-standard CALs were included during a 30-s submaximal isokinetic protocol (1). However, these studies primarily relied on short-duration protocols and did not quantify endurance TT completion or self-paced performance metrics that better reflect race demands. Consequently, the practical implications of small, commercially available CAL variations for endurance-based cycling TT performance remain unclear, as much of the existing

evidence comes from relatively short-duration, maximal-power protocols using unrealistically wide CAL ranges.

Furthermore, in terms of evolving technology, indoor cycling with augmented reality (AR) software is gaining more attention due to several benefits such as weather independence, the ability to visually mimic real race roads, and the capability to track numerous cycling metrics in a controlled setting (5,7,13,18,26,31). Because AR-based indoor cycling enables repeatable, standardized TT assessment, it offers a practical approach to test whether small, commercially available CAL differences translate into meaningful endurance performance changes. Previous research has demonstrated that virtual cycling platforms can provide benchmark values such as power output during cycling TT performance (6,7,18). Additionally, AR software could be the powerful tool for simulating the realistic race experience while measuring additional data which may be difficult to obtain from a real race situation (26,31). However, the extent to which commercially available CAL differences influence cycling TT performance within an AR-simulated indoor cycling context remains unclear.

Therefore, the purpose of this study was to identify whether cycling metrics and cycling TT performance using smart bike and AR software are affected by different CALs. We hypothesized that the shorter CAL would reduce time to completion sequentially and influence cycling metrics (i.e., cycling power, cadence, etc.) on the designated virtual route. Ultimately, we hoped to provide practical insights into optimizing CAL to enhance TT performance and reduce unnecessary mechanical and/or physiological strain or injury risk during endurance cycling.

2 Material and Methods

2.1 Participants

Recreationally trained subjects (n = 14; 8 males, 6 females) voluntarily participated in the study (Table 1). The inclusion criteria were [1)] subjects must be over 18 yr old, [2)] subjects must be comfortable riding a bike at least 30 min a day, [3)] subjects must not have any injury that would interfere with their ability to ride a bike, [4)] subjects cannot be pregnant or think they are pregnant. When subjects met all the inclusion criteria as well as were willing to participate in, they provided written informed consent, the physical activity readiness questionnaire for everyone (PAR-Q+), and health history questionnaire. Subjects were allowed to ask any questions at any time regarding the research process. Research protocol was fully approved by the hosting institution's Institutional Review Board of the hosting institution (#2023-041).

Table 1. Descriptive statistics of subjects

	Total (n = 14)	Male (n = 8)	Female (n = 6)
Age (yr)	21.4 ± 1.5	21.9 ± 1.6	20.7 ± 1.0
Height (m)	1.73 ± 0.11	1.80 ± 0.08	1.64 ± 0.08
Body mass (kg)	77.8 ± 17.3	87.8 ± 12.9	64.6 ± 13.2
BMI (kg·m^{-2})	25.8 ± 4.5	27.0 ± 3.0	24.3 ± 5.9
Lower Limb Length (cm)	89.0 ± 6.8	91.6 ± 6.7	85.5 ± 5.5

Note: Data are represented as mean and SDs

2.2 Protocol

Subjects participated in three testing sessions, each lasting approximately 40–45 minutes. During these sessions, each subject completed three submaximal cycling TTs with three different CALs (i.e., 165, 170, and 175 mm) using a smart bike (KICKR Bike, Wahoo, Atlanta, GA) integrated with augmented reality software (Rouvy, Vimperk, CZ) (Figure 1), which provided a controlled, simulated environment.

Figure 1. Smart bike and changes in crank arm length options.
Note. Shorter CAL is on the top hole (165 mm), then increases by 2.5 mm to the bottom hole (175 mm).

The CAL order across each subject's three sessions was randomized in a balanced crossover design. For all sessions subjects were instructed to arrive wearing appropriate exercise attire such as breathable clothing and closed-toe shoes. They were also asked to refrain from alcohol consumption, caffeinated beverages, and intensive lower-body exercise for at least 24 hours before testing, and to perform to the best of their ability during the experimental trials.

During the initial visit, baseline anthropometric data were collected. Body mass (kg) and height (m) were measured using a physician's beam scale, and a wall-mounted stadiometer respectively. Body mass index (BMI: $kg \cdot m^{-2}$) was calculated from the body mass and height. Lower limb length was measured from the greater trochanter to the lateral malleolus using a Gulick anthropometric measurement tape. Following these measurements, a comprehensive bike fit was performed according to each subject's body size and preferences. Key bike fitting parameters (i.e., stack, reach, setback, saddle height, and knee joint angle) were recorded using a Gulick anthropometric measurement tape and goniometer.

Each of the three sessions began with a standardized warm-up protocol to ensure consistency between subjects. This protocol consisted of dynamic stretches (e.g., jumping jacks, butt kicks, forward and lateral leg swings) and a 5-min cycling warm-up at a self-selected pace using a 170 mm CAL. Following the warm-up, subjects completed one of three submaximal cycling TTs using three CALs in each session. The trials were conducted on a smart bike (KICKR Bike, Wahoo, Atlanta, GA) integrated with AR software (Rouvy, Vimperk, CZ). All trials were conducted on the same virtual cycling route, which covered a distance of 11.65 km with a total elevation gain of 34.1 m (Figure 2).

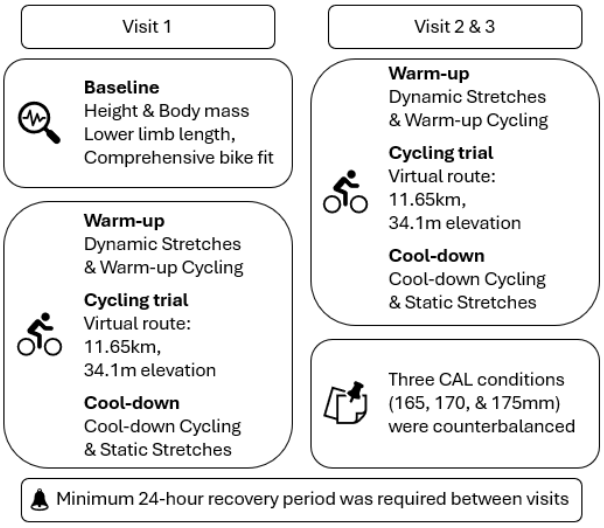

Figure 2. Overview of the study design and experimental procedure.

Prior to each trial, subjects were fitted with a heart rate strap (HRM-Tri™, Garmin, Olathe, KS). They were instructed to ride the smart bike, equipped with flat pedals, at a pace corresponding to 13–15 ("Somewhat hard" to "Hard") on Borg's 6–20 Rating of Perceived

Exertion (RPE) scale (2) and to remain seated throughout each trial. To ensure adherence to the target intensity, the research team continuously monitored power output, cadence, and heart rate. Additionally, while it is not entirely representative of real-world racing, subjects were instructed to remain seated on the saddle throughout the experimental sessions and were not permitted to change gears to ensure a consistent, controlled protocol across subjects. Subject RPE was verbally assessed every five minutes using the 6 – 20 Borg's scale (2). No verbal encouragement was provided to subjects during the trials.

Following each session, subjects performed a standardized 5 min cool-down cycling at a self-selected pace on the same bike, followed by static stretches for the quadriceps, hamstrings, and calf muscles. A minimum recovery period of 24-hr was mandated between sessions to mitigate any potential muscle soreness or residual fatigue.

2.3 Statistical Analysis

A repeated measures ANOVA was performed to see if there were any differences between the three CAL trials in various cycling performance metrics, including cadence (rpm), pace ($m \cdot s^{-1}$), power output ($Watts \cdot kg^{-1}$), TT performance (min), energy expenditure (kJ), average heart rate (bpm), and perceived exertion (RPE). Data were expressed as mean ± SD. The assumption of normality was assessed using the Shapiro–Wilk test, and sphericity was evaluated with Mauchly's Test. When the assumption of sphericity was violated, as indicated by Mauchly's Test, the Greenhouse-Geisser correction was applied. *Post hoc* comparisons were conducted using the Bonferroni adjustment when a significant main effect was identified. Effect sizes were reported as partial *eta* squared (η^2_p), with values interpreted as small (0.01), medium (0.06), and large (0.14). The significance level was set *a priori* at $p \leq 0.05$, and all analyses were performed using SPSS 29 (IBM BM Corp, Armonk, NY).

3 Results

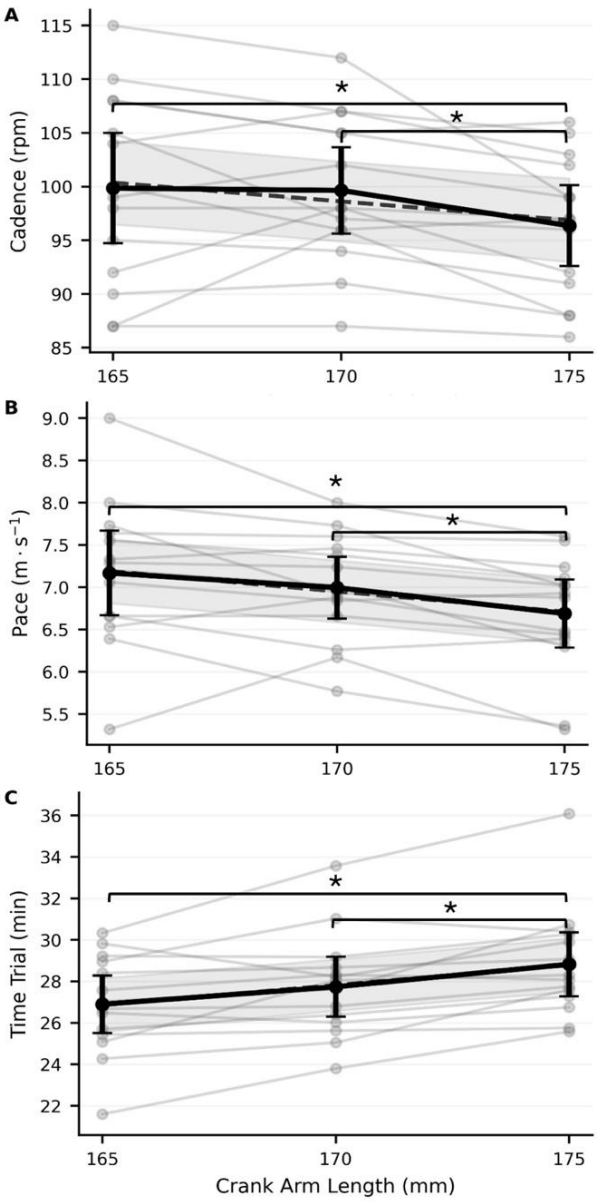

Figure 3. Crank arm lengths on cadence, pace, and time-trial performance.
Note. Panels A–C depict cadence (rpm), pace ($m \cdot s^{-1}$), and time trial time (min), respectively. Grey lines show individual participants; the thick black line and points show the mean with 95% confidence intervals. The dashed line with the shaded band shows the mixed-effects model trend, including a random intercept for each participant, with 95% confidence intervals.

Cadence had a significant main effect across CALs ($F_{2,26}$ = 6.05, p < 0.01, η^2_p = 0.318). Specifically, *post hoc* comparisons revealed that cadence was significantly lower with the 175 mm CAL compared to both 165 mm (p = 0.037) and 170 mm (p = 0.017), while no significant difference was found between 165 mm and 170 mm (p = 1.00) (Figure 3A).

Pace was also significantly influenced in main effect by CALs ($F_{2,26}$ = 9.65, p < 0.001, η^2_p = 0.426). In line with the cadence findings, pace was significantly slower with the 175 mm CAL compared to both the 165 mm (p = 0.005) and 170 mm (p = 0.006) lengths; there was no significant difference between the 165 mm and 170 mm lengths (p = 0.564) (Figure 3B).

In addition, TT performance demonstrated a significant main effect across CALs ($F_{2,26}$ = 12.37, p < 0.001, η^2_p = 0.488). Subjects required more time to complete the TT when riding with 175 mm crank arms relative to both 165 mm (p = 0.004) and 170 mm (p = 0.015) (Figure 3C). Although there was a trend toward slower completion with 170 mm compared to 165 mm, this did not reach significance (p = 0.084).

Conversely, no statistical main effects of CALs were detected for cycling power ($F_{2,26}$ = 0.638, p = 0.54, η^2_p = 0.047), energy expenditure ($F_{2,26}$ = 0.837, p = 0.44, η^2_p = 0.061), heart rate ($F_{2,26}$ = 0.497, p = 0.59, η^2_p = 0.037), and RPE ($F_{2,26}$ = 0.392, p = 0.29, η^2_p = 0.029) (Table 2).

Table 2. Descriptive summary of key dependent variables under three conditions

	*Cadence (rpm)	*Pace ($m \cdot s^{-1}$)	*TT (min)	Power ($Watts \cdot kg^{-1}$)	EE (kJ)	HR (bpm)	RPE
165 mm	99.86 ± 8.88	7.17 ± 0.87	26.90 ± 2.40	83.64 ± 20.14	132.79 ± 28.55	148.47 ± 12.85	12.86 ± 1.24
170 mm	99.64 ± 6.96	7.00 ± 0.63	27.74 ± 2.50	78.93 ± 17.32	125.29 ± 23.16	150.57 ± 12.08	13.20 ± 0.89
175 mm	96.36 ± 6.52	6.69 ± 0.70	28.82 ± 2.66	80.71 ± 13.88	125.00 ± 27.00	147.96 ± 14.42	12.89 ± 1.62

Note: Data are represented as mean and SDs
Asterisks indicate a significant main effect (p < 0.05)

4 Discussion

Cycling with a smart bike integrated with AR software provides a controlled and interactive platform for performance testing and indoor training. Although this setup does not fully replicate real-world cycling, it provides a controlled yet immersive simulation that mimics actual race routes and environmental conditions (7). In this study, we observed that both 165 and 170 mm CALs resulted in shorter completion times with higher cadence and faster pace compared with 175 mm CAL, while other physiological and mechanical variables remained unchanged. These findings partially support our hypothesis, as time to completion improved significantly, however not all performance metrics were influenced by CAL.

Our findings are consistent with prior research that showed that 165 and 170 mm CALs were equally efficient compared with 175 mm during moderate-intensity cycling (i.e., 60% of VO_2max) in trained road cyclists (15), Similarly, a previous investigation found that small CAL variations (i.e., 165-172.5 mm) did not significantly influence cycling power, indicating that minor adjustments may have limited impact on mechanical output (24). A key distinction of our study from earlier work lies in both methodology and population. Whereas many previous studies have primarily focused on experienced or elite cyclists in traditional laboratory settings, we tested healthy, active but non-elite cyclists or triathletes using this smart bike integrated with AR software that dynamically adjusted resistance based on course elevation to better

replicate race-like conditions. By focusing on this population, we aimed to provide findings relevant to recreational cyclists and novice triathletes, for whom efficiency, cardiorespiratory health, and reduced fatigue are often prioritized over maximal performance.

In addition, a previous study demonstrated that novice cyclists may benefit from choosing a shorter CAL (i.e., 145 mm) rather than a conventional CAL (i.e., 175 mm) during 30-min cycling at a moderate intensity (i.e., 60% of VO_2peak, blood lactate: 2.7–2.8 mmol/L, heart rate: 132–144 bpm) (3). This may not directly align with our observations, not only because of the limited option of adjusting CALs in 2.5 mm increments between 165 and 175 mm (Figure 1), but also our study focused on the small changes within standard CAL ranges. However, it also supports the idea that a novice cyclist could consider choosing a shorter CAL to cycle more economically without sacrificing other physiological parameters such as blood lactate, minute ventilation, and heart rate.

Another study investigated the effect of combinations of the CALs (i.e., 127, 140, 152, 165 mm) and seat tube angles (i.e., 60, 65, 70°) on lower extremity kinematics, muscle activities, and metabolic responses in healthy young adults without any competitive cycling experiences (30). The study observed that there were no meaningful differences in metabolic responses using relatively shorter CALs than standard ones. Together with our findings, this suggests that shorter CALs may be a viable option for inexperienced riders (3,30). However, the practical benefit of reducing CAL below 165 mm remains unclear and may depend on individual fit and event demands.

Another consideration of selecting CAL will be the proportion of the lower body length (8,17). Previous study suggested that the optimal CAL for maximizing power output may be individualized based on anthropometric measures, approximately 20% of the distance between standing height and seat height, or 41% of the tibial length measured from the knee cleft to the lateral malleolus (17). We measured the lower limb length from the greater trochanter to the lateral malleolus (i.e., total: 88.96 ± 6.76, male: 91.56 ± 6.74, female: 85.50 ± 5.47). Our subject's CAL-to-limb ratios (i.e., 18.6% for 165 mm, 19.1% for 170 mm, and 19.7% for 175 mm) are closely aligned with the previous study. However, our research did not individualize CAL based on lower-limb length due to the limited CAL options available on the smart bike.

4.1 Smallest Worthwhile Change (SWC)

The SWC is the minimum change in a measurement that is considered practically meaningful even though the statistical analysis reveals no significant differences (5,9,22). SWC was calculated as 0.2 × the mean standard deviation across the three CAL conditions, representing a small, standardized effect (9). If the absolute difference ($|\Delta|$) between conditions exceeds the calculated SWC, it may be considered practically meaningful in real-world settings. Otherwise, it is considered trivial both statistically and practically.

We observed statistically significant main effects on three dependent variables: cadence (rpm), pace ($m \cdot s^{-1}$), and TT performance (min). Although pairwise comparisons showed no statistically significant differences between the 165 and 170 mm CAL conditions in cadence, pace, and TT performance, the SWC analysis provided additional insight. Several variables exceeded the SWC threshold between 165 and 170 mm, with the most practically relevant differences observed in pace and TT time (Table 3).

Table 3. Smallest worthwhile changes (SWC) and differences in mean values between conditions

	Cadence (rpm)	Pace ($m \cdot s^{-1}$)	TT (min)	Power ($W \cdot kg^{-1}$)	EE (kJ)	HR (bpm)	RPE
SWC	1.49	0.15	0.51	3.42	5.25	2.62	0.25
165 – 170 mm	0.21	0.17*	0.87*	4.71*	7.50*	2.10	0.34*
165 – 175 mm	3.50*	0.48*	1.90*	2.93	7.79*	0.51	0.03
170 – 175 mm	3.29*	0.31*	1.02*	1.79	0.29	2.61	0.30*

Note. The smallest worthwhile change (SWC) was calculated as 0.2 multiplied by the mean SD of the three conditions. Comparison values are absolute mean differences (|Δ|) between conditions.
Asterisks indicate a meaningful SWC between CAL conditions.

Specifically, the SWC for pace was 0.15 $m \cdot s^{-1}$ and the observed difference between 165 mm and 170 mm CALs was 0.17 $m \cdot s^{-1}$ which is slightly above the SWC threshold, suggesting a meaningful improvement. Similarly, the SWC for TT performance was 0.51 min (equivalent to 30.6 seconds), while the observed SWC difference between 165 and 170 mm CALs was 0.87 min (equivalent to 52.2 seconds), exceeding the SWC threshold despite the lack of statistical significance ($p > 0.05$). However, the SWC difference in cadence between the 165 and 170 mm CALs was trivial as well as not statistically significant ($p > 0.05$), even though cadence is closely linked to pace, cycling power, and ultimately TT performance from a practical standpoint. Collectively, these findings highlight that cyclists and practitioners should consider both statistical and practical significance when selecting CAL for endurance cycling. Even small, non-significant changes statistically in pacing or TT performance may accumulate meaningful performance benefits in competitive settings, reinforcing the utility of SWC analysis in applied sport science decision-making.

4.2 Role of Augmented Reality in Performance Assessment: Smart Bike Integration

Cyclists often use indoor bike trainers paired with bike computers (e.g., Garmin, Wahoo) to monitor cycling power metrics and share their achievements on social media platforms such as Strava (7,18). Even after the COVID-19 pandemic, many cyclists continue to train using augmented or virtual reality platforms (e.g., Zwift, ROUVY) to avoid extreme weather conditions such as cold winters, rain, or hot and humid days (5). These platforms also help simulate real-race experiences, familiarize cyclists with course layouts through pre-recorded videos, enhance motivation, and increase daily or weekly physical activity levels (7,13,18,26).

In actual race situations, maintaining target power output and being familiar with race routes are crucial for success. For example, cyclists can conserve energy for steep climbs, plan gear changes, manage nutrition, and anticipate winding turns when they are familiar with the course through AR software. In our study, subjects were initially exposed to AR software and a smart bike that adjusted resistance according to course elevation while providing visual feedback. Anecdotally, subjects reported that this experience was more enjoyable than using a typical indoor cycle ergometer, even though they were not regular cyclists. This enhanced engagement may have influenced perceived exertion. Subjects were instructed to cycle at a subjective intensity of "somewhat hard" to "hard" (RPE 13–15). However, the reported RPE values were slightly lower, ranging from 12–13 (Table 2), which corresponds to an intensity between light and somewhat hard. Interestingly, exercise heart rates were approximately 148–150 bpm (Table 2), suggesting a discrepancy between perceived and actual physiological load. A plausible explanation is that the AR environment may

have led subjects to perceive the exercise as less demanding than it actually was by providing real-time metrics and enhancing engagement through features such as avatars, ghost riders of past performances, and other interactive visual elements (13,26,31).

Despite the strengths of this study, several factors should be considered when interpreting the findings. The cycling distance used in this study (11.65 km; time to completion approximately 26–28 minutes) was considerably shorter than typical cycling race events, including triathlons. For instance, this distance represents roughly half of the cycling portion (i.e., 20 km) in a sprint triathlon. The relatively short duration may have limited the extent to which physiological and biomechanical responses to small changes in CAL were observed.

Although all subjects were physically active, they were not elite or highly trained cyclists. Due to unfamiliarity with the narrow, rigid saddle, some subjects anecdotally reported discomfort, which may have influenced riding posture or effort. Furthermore, subjects used flat pedals without cleats or straps and were required to remain seated and refrain from changing gears. Although these constraints did not fully replicate real-world cycling, they were implemented to ensure a consistent protocol and reduce between-subject variability in technique and pacing. The use of flat pedals occasionally led to minor foot slippage, particularly during downhill sections where resistance changed with the terrain.

Therefore, future research should test longer-distance protocols (e.g., ≥20 km, comparable to a sprint triathlon or greater) under more ecologically valid conditions that allow gear shifting and changes in riding position. These studies should include experienced cyclists and triathletes to determine whether the advantages of shorter CALs persist in competitive settings. Studies should also incorporate individualized crank-length fitting and targeted biomechanical and neuromuscular assessments to refine applied guidance for optimal CAL selection.

5 Practical Applications

This study found that shorter crank arms (i.e., 165–170 mm) produced higher cadence, faster pace, and shorter completion times than 175 mm (175-mm condition), while power output, energy expenditure, heart rate, and perceived exertion remained similar. Based on the smallest worthwhile change (SWC) analysis, these recommendations are most applicable to recreational cyclists and novice triathletes. However, the smart bike–AR setup may also be valuable for experienced cyclists and triathletes as a reproducible tool for indoor training and pacing practice. Within standard commercial ranges, selecting slightly shorter crank arms may improve cycling efficiency and comfort during prolonged efforts. For indoor cycling training using a bike trainer, shorter crank arms may help conserve energy during sustained cycling work and may improve comfort and reduce localized fatigue, making it easier to maintain target cadence and pacing across longer durations. They may also support the accumulation of training volume and the practice of pacing/race strategies while monitoring power and other physiological metrics using wearable devices. Coaches and practitioners should prioritize individualized crank-length selection based on comfort, anthropometrics/fit, and training goals rather than defaulting to standard configurations. Finally, pairing a smart bike with an augmented-reality cycling platform offers a reproducible, race-like setting (e.g., elevation changes, turns, and immersive visual feedback) for tracking performance and supporting training and race preparation.

Funding: This research received no external funding.

Acknowledgments: The authors would like to acknowledge all subjects who participated in this research.

Conflicts of Interest: The authors declare no conflict of interest.

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