Cycling Biomechanics Optimization—the (R) Evolution of Bicycle Fitting

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Abstract

Optimal bicycle configuration has been the topic of numerous studies. A majority of these have investigated the optimal saddle height and have used either static kinematics or two-dimensional kinematic measurements. Other joints, such as the hip, shoulder, and elbow joint, have not been investigated to any meaningful extent. There is, therefore, a paucity of data describing the optimal position of the upper body and pelvis in cycling. More recently, it has been recommended that bike fitting be conducted in a dynamic functional manner, as kinematics can be influenced by cycling workload. Full-body three-dimensional kinematics and saddle pressure are newer modalities available to the clinician. This review of the literature investigates the current research pertaining to the configuration of all components of the bicycle, from static methods to dynamic methods, and related to optimal performance and injury prevention. Setting the saddle height using the Holmes static method is optimal for injury prevention and performance. Guidelines for optimal bicycle configuration should take into account the training intensity when assessing kinematics as compensatory lower-limb kinematics occur during higher-power outputs. Optimal KFA using dynamic measurements should range from 33° to 43° at low intensity to 30° to 40° at high intensity when measured at the bottom dead center crank position. Saddle pressure mapping should ideally be performed at an intensity similar to what cyclists will encounter during the majority of their training and racing. Reference values and recommendations for dynamic assessments are still required for all other joints. Furthermore, intrinsic factors, such as training load and flexibility, which may affect bicycle configuration and performance, should be investigated to assess how these may influence the optimal bicycle configuration.

Introduction

Bicycle fitting is defined as "the detailed process of evaluating the cyclist's physical and performance requirements, and systematically adjusting the bicycle to meet the cyclist's goals and needs" (1). Bicycle configuration can have an influence on the cyclist's performance and perception of comfort (2). Cyclists have been searching for the optimal position to gain power while remaining injury free on their bicycles long before the science has evolved.

The bicycle fitting industry has grown exponentially, with the title "bicycle fitter" becoming an established career option. However, this means that anyone can call themselves a bicycle fitter, regardless of their skills, knowledge, or expertise (3). This has led to the development of the International Bicycle Fitting Institute in 2014, which acts as an international organization to develop a global standard for the bicycle fitting industry. The organization protects not only the qualified bicycle fitters but also the cyclists, ensuring that they receive the expertise, skills, and services they expect.

With the advancement of technology, new methods to optimize bicycle configuration have developed considerably in the last 5 to 10 years. Previous methods were limited to anecdotal formulae for assessing saddle height and other fit parameters and technology limited assessment to static or two-dimensional (2D) kinematics. The advent of three-dimensional (3D) kinematics, pressure mapping technology, and, more recently, inertial motion sensors have allowed bicycle configuration to adopt a progressively more scientific approach in comparison to the "art" it was back in the early days of cycling.

While there are numerous studies which have investigated the optimal saddle height for performance and injury prevention (Table 1), the saddle only forms one of the three contact points for the cyclist with the bicycle. In addition, a majority of these studies have utilized static kinematic methods. The handlebars, cranks, and pedals also can be adjusted to optimize a cyclist's position. Previous research on the correct positioning of these components is based solely on personal preference and opinion and is not evidence-based (2,13,14). With the advancement of technology, practitioners are now able to record kinematics using 3D motion capture. Dynamic

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Table 1.
Studies investigating optimal saddle height.

Study	Method of Setting Saddle Height	Outcome Measures	Participants/Paper Type	Main Results and Notes	Recommendations for Setting Static Saddle Height
(4)	Percentage of inseam length	Time to exhaustion during constant load cycling	100	109% inseam length minimized time to exhaustion	109% inseam length
(5)	100%, 103%, 106%, 109%, and 112% of inseam length	$\dot{V}O_2$, VCO_2, V_E, HR	5	Maximal power achieved at saddle height of 103%–104% of inseam length	Saddle set at 103%–104% inseam length resulted in maximum power output
(6)	95%, 100% and 105% Trochanteric height	$\dot{V}O_2$	10 women	Economy at 100% of trochanteric leg length is improved in comparison to 95% or 105%	100% Trochanteric saddle height most economical
(7)	KFA	Lower-extremity overuse injuries	Review	To minimize knee joint load, aim for 25–35° KFA	25°–35° KFA
(8)	109% Inseam length (Hamley and Thomas) LeMond method Heel-Toe method	To determine which method best fits into the recommended 25–35° KFA	14 male cyclists 5 female cyclists	No significant difference between Hamley and Le Mond method. Significant difference between Hamley and heel-toe method. Hamley method fell into the 25°–35° KFA 55% of the time.	Holmes method, 25°–35° KFA
(9)	25° KFA 35° KFA 109% Inseam length (Hamley and Thomas)	Anaerobic Power	9 male trained cyclists 3 nontrained male cyclists 15 female nontrained cyclists	a) Using 109% inseam length to set saddle height, fell outside 25°–35° KFA 63% of the time. b) When outside recommended KFA, there was a loss in power, especially at lower saddle heights. c) When within recommended KFA there was no difference in power.	Holmes method, 25°–35° KFA
(10)	25° KFA 35° KFA 109% Inseam length (Hamley and Thomas)	$\dot{V}O_2$	5 male cyclists 2 male noncyclists 9 female noncyclists	A 25° KFA produced a significantly lower $\dot{V}O_2$ compared to 35° KFA and 109% inseam length.	For increased economy, a KFA closer to 25°
(11)	25° KFA 35° KFA 109% Inseam length (Hamley and Thomas)	$\dot{V}O_2$ Anaerobic power	11 well trained males	Economy was better at 25° KFA compared to 35° and 109% inseam length. Power production was better at 25° compared to 109% inseam length.	For better economy and power production recommends a KFA closer to 25°
(12)	Review of literature	a) Comparison of lower leg length measurements and knee angle methods. b) Effects of saddle height on performance. c) Effects of saddle height on knee injury risk	Review	a) The KFA method recommended b) Saddle height set to the Holmes method has better evidence for improved performance. c) A knee flexed at 25°–30° has been related to lowering the knee joint load and, thus, injuries.	Holmes method, 25°–35° KFA

Table 2.
Workload effects on lower-limb joint kinematic.

Study	Method of Setting Saddle Height and Measuring Hip Angle	Aims of Study	Testing Method	Participants	Main Results and Notes
(15)	Matched to own bicycle. Vicon Hip angle measured relative to horizontal and not true hip angle	Compare joint kinetics and kinematics during an incremental cycling test to exhaustion	60%, 75%, 90%, 100% PO_{max}	11 competitive male cyclists	Ankle DF increased at 100% PO_{max} Hip extension increased at 100% PO_{max}
(16)	Bicycle configuration not specified. Vicon. Hip angle measured relative to horizontal and not true hip angle	Analyze the joint forces and kinematics during cycling to exhaustion	Workload set at PO_{max} until exhaustion	10 well-trained male cyclists	Ankle DF increased with fatigue Hip and knee more extended with fatigue
(17)	Own bicycles attached to a flywheel	To determine whether changes in 3D lower-limb kinematics occur during the drive phase in sustained TT cycling	Six 10-min work periods: 8 min at 88% OBLA, 90-s effort phase at 140% of OBLA, followed by 30-s rest at 60% OBLA	10 experienced male cyclists	Increase into hip extension Increase into ankle DF
(18)	Matched to cyclist's bicycle. Nonathletes set saddle height according to trochanteric height to floor. Hip angle measured relative to horizontal and not true hip angle One high speed camera perpendicular to motion plane	a) Compare cyclists and noncyclists lower-limb kinematics b) Assess the effects of different workloads on joint kinematics in cyclists and noncyclists	VT1 − 25 W VT1 + 25 W VT2 − 25 W VT2 + 25 W PO_{max}	15 athletic males 14 nonathletic males	Ankle DF increased at maximal workload. Increased hip extension at PO_{max} Greater forward body position was observed at PO_{max} compared with submaximal stages.
(19)	Configured to elicit ~30° of KFA with crank aligned with seat tube angle using a goniometer Vicon	Compare 3D joint and segment kinematics between competitive and recreational cyclists across different workloads	30 s at workloads of 65%, 75%, 85%, and 95% PO_{peak}	12 competitive male cyclists 12 recreational male cyclists	No workload effects were observed in any of the assessed variables. Recreational cyclists presented larger ranges of motion for lateral spine inclination and spinal rotation compared with competitive cyclists.
(20)	Freely chosen saddle height. 3D Vicon.	Assessed whole body 3D kinematics at 60%, 80%, and 90% of maximal heart rate	60%, 80%, and 90% of maximal heart rate.	17 well trained cyclists	Ankle DF and knee more extended with increased intensity. Lumbar and thoracic flexion, elbow flexion and thoracic lean angle increased with intensity.

DF, dorsiflexion; TT, time trial; OBLA, onset of blood lactate accumulation; VT, ventilatory threshold.

methods of assessing a cyclist's position may provide more relevant data in comparison to static methods. However, a majority of the dynamic kinematic instruments have not been assessed for validity and reliability.

This review of the literature investigates the current research pertaining to the configuration of all components of the bicycle, from static methods to dynamic methods, and related to optimal performance and injury prevention.

Optimal Static Saddle Height Configuration for Performance and Injury Prevention

A number of studies have assessed optimal saddle height configuration. Empirical methods of setting saddle height have been used by cyclists for decades (Table 2). One of the most basic methods of setting saddle height, which can be used by cyclists with limited technological knowledge or equipment, is known as the heel-toe method. The cyclist sits on the saddle and places their heel on the pedal at bottom dead center (BDC). The saddle height is adjusted until the knee is locked in an extended position. Greg LeMond, a famous cyclist and later coach, set his saddle at a height of the inseam multiplied by 0.883 (21). Even though this method was tested in the wind tunnel and was a very popular method at the time, with new equipment, such as clipless pedals, it has now become rather outdated (22).

Hamley and Thomas (4) were perhaps the first to publish scientific saddle height recommendations. They proposed that for optimal cycling performance, saddle height should be adjusted, whereby the distance from the pedal surface to the top of the saddle as measured through the seat tube should equate to a value equal to 109% of the leg inseam length. Subsequently, a method of setting the saddle height according to trochanteric leg length was published (4). The effect of saddle height changes on oxygen consumption was investigated during a continuous work protocol from 50 to 200 W, with five different saddle heights tested. It was concluded that a saddle height of 100% or 103% of the trochanteric leg length was most efficient, and a range of 103% to 104% of trochanteric height was recommended to optimize performance (5). A similar study investigated saddle heights configured at 95%, 100%, and 105% of trochanteric height (6). It was determined that the saddle set at 100% of trochanteric height was the most efficient, compared with 95% and 105% trochanteric height.

Since then, studies have focused on various experimental methods of setting saddle height to optimize muscle activity (23,24) or compressive forces through the knee (25). These are described in detail in the review (12).

Perhaps, the most commonly used method to date is the Holmes method (7). This method recommends that the knee flexion angle (KFA) is set between 25° and 35° to limit overuse knee injuries. Excessive KFA may increase patellofemoral joint reaction stress, resulting in patellofemoral overuse injuries while excessive saddle height may impose stress on the posterior chain resulting in hamstring overuse injury or result in compensatory changes, such as pelvic movement which can predispose to saddle sores or lower back pain, or excessive ankle plantar flexion which may result in an Achilles tendon injury (7). KFA is measured with a goniometer (GM) with the cyclist in a stationary position, with the pedal horizontal and the crank arm in the lowest or 6 o'clock position and the pedal surface in a horizontal orientation (to standardize the ankle joint position), also known as the BDC position. This is an easy and inexpensive measurement to perform (14).

Peveler et al. (8) compared various methods of setting saddle height. The inseam of the leg was measured and used to set the saddle according to both the Hamley method (inseam × 1.09), and the LeMond method (inseam × 0.883). Third, the saddle was configured as per the heel-toe method described earlier. In each of these positions, the KFA was measured to compare it with the Holmes method (KFA of 25° to 35°). The first three methods fell into the Holmes recommendation KFA 55% to 70% of the time. They concluded that for cyclists who were not prone to knee injury the saddle height be set at 109% inseam length for optimal performance, and those who may be susceptible to injury, to remain within the 25° to 35° range, compromising on economy, yet reducing the risk of injury.

In a further study by Peveler et al. (9) they investigated the effect of saddle height on anaerobic power production. Once again, the Hamley and Holmes methods were compared, with the protocol repeated at three saddle heights; 25° KFA, 35° KFA, and at 109% of inseam length. There was no significant difference between the groups for peak power or mean power, and further analysis was done by dividing the subjects into those that fell within the recommended 25° to 35° KFA and those that fell outside the recommended range when using the 109% inseam saddle height method. There was a general loss in power in those that fell outside of the recommended range, especially at saddle heights that elicited a KFA greater than 35°. There was no significant difference between saddle heights with less than 25° KFA. In a follow up study, $\dot{V}O_2$ was significantly lower at 25° KFA (signaling greater economy) compared with the 35° KFA or 109% inseam (10). In an additional study, a saddle height set at 25° KFA was more economical in comparison to a saddle height set at 35° KFA or at 109% inseam (11). From this series of studies, it was determined that setting a saddle height using a static method at 25° to 35° KFA is optimal for injury prevention and performance, and it was recommended that a KFA closer to 25° be used to enhance performance (9–11). A summary of the more prominent studies investigating saddle height are shown in Table 1.

Static Kinematic Recommendations for All Body Joints and Bicycle Components

To optimize performance and prevent injury, saddle height has been recommended to be set using static techniques at a KFA of 25° to 35° when the crank arm is at BDC position (9). To date, there have been no other researched ranges for optimal joint angle ranges for the other joints of the body. There are guidelines for ankle and elbow ranges but these are based on personal opinion and not based on scientific data (2,13,22). Complicated formulae to determine saddle setback, handlebar reach, and handlebar drop have been investigated (14,26); however, most bicycle fitting experts have suggested that the final position should be based on comfort and what is considered "visually acceptable." An immediately apparent limitation to these formulae is that they do not take into consideration individual anthropometrics, flexibility, training load, and history nor the specific cycling discipline, nor do they provide any objectively quantifiable outcomes (9).

It is well known that excessive handlebar reach or drop can cause overuse injuries in cyclists (27,28). Excessive handlebar drop may predispose the rider to lower back pain due to increased lumbar flexion. Similarly, a saddle set too far forward or too far rearward can cause lower-extremity injuries as a result of changes in muscle recruitment patterns or knee joint ROM. However, there are currently no scientific studies to guide general norms for these parameters nor for joints other than the knee while on the bicycle.

Holliday et al. (*29*) compared static to 3D kinematics and published mean joint angle values for the ankle, knee, hip, shoulder, and elbow joints for GM, digital inclinometer (IM), and 3D kinematics for a group of 19 well-trained male cyclists. They measured hip and shoulder angle utilizing segments through the lower lumbar spine and upper thoracic spine, respectively, and these data may therefore represent the only accurate data for both static and dynamic joint angle means for the hip and shoulder joint.

However, research using a larger cohort which also includes recreational athletes is required to establish more accurate reference values to guide clinicians going forward.

Dynamic Kinematics and Newer Technology in Cycling Biomechanics

Prior to the year 2000, dynamic studies have exclusively used photographic or video analysis for dynamic assessment, and a majority of the studies have assessed only the sagittal plane kinematics (30). Kinematics measured in 3D are considered more accurate compared with 2D systems, as the 2D systems cannot measure movement in the axial plane (31). However, 3D kinematic systems have not been used in practice due to their expense. Newer, affordable, high-quality 2D or 3D motion capture systems are becoming available (STT Systems, San Sebastian, Spain; Bioracermotion, Tessenderlo, Belgium).

The reliability and validity of 3D kinematic systems for cycling in comparison to static techniques has recently been assessed (29). Measures were taken statically with a standard GM and IM, and dynamically using an 8-camera 3D motion capture system (Vicon, Oxford, United Kingdom). All three instruments were found to be valid and reliable with a low Typical Error of Measurement (TEM) for all of the measured joints. The study demonstrated a positive correlation between GM and IM measures for all joints. The 3D motion analysis utilizes different landmarks for most joints and produces different means for all joints except the knee, shoulder, and elbow. This is particularly relevant to the hip joint. For example, 3D motion capture uses a perpendicular line bisecting the anterior-superior-iliac spine and posterior-superior-iliac spine, and a line bisecting the knee joint center and greater trochanter to determine hip flexion angle, whereas static measures of the hip joint define the hip angle as the angle subtended by the area expanding below the iliac crest from the third lumbar vertebra to the sacrum to the line bisecting the greater trochanter and lateral femoral condyle.

Muscles which span this joint are a major contributor to power production in cycling. A subsequent study has demonstrated that altered kinematics occur in the lumbar and thoracic spine with increasing intensity (20). Dynamic methods of assessing hip and shoulder angles were previously measured with simplistic methods, not taking the spinal flexion into account (32). These methods undermeasure both hip and shoulder flexion and do not capture the changes that occur in these joints with changes in intensity. It is, therefore, important that further research utilizing 2D and 3D motion capture develop reference values for all joints based on relative workload to aid clinician-based bicycle configuration.

Dynamic measurements of KFA also are confounded by changes which occur from static to dynamic measurement and by changes in workload.

With advances in technology, we are now also able to measure the pressure at the interface between the cyclist and the saddle as well as at other contact point areas (Gebiomized®, Munster, Germany). The reliability and validity of bicycle seat interface pressure measurements have been previously determined (33). The saddle is typically divided into three zones to differentiate anterior and posterior left and right. It was concluded that the within-trial reliability was excellent for both mean and peak pressure values. The between-trial saddle pressures showed moderate to excellent reliability for all areas of the saddle, except anterior saddle pressure, which showed poor reliability. At present, no studies have been conducted to assess how changes in the configuration of the bicycle affect the saddle pressure indexes, and there are no defined norms for these variables.

Cycling-related pressure mapping has further advanced to include handlebar pressure and foot pressure dynamic assessment. This has enabled bicycle fitters to assess all contact points concurrently and to provide insight into interventions, such as custom inner soles and orthotics. However, there are no validity or reliability studies nor normative data to guide the use of these novel instruments.

Changes in Lower-Limb Kinematics with Intensity

With more bicycle fitters using dynamic bicycle fitting methods, it is important to establish new normative ranges for joint angles, as static measurements do not always agree with dynamic measurements (29,30). Kinematics of the knee and ankle joints change significantly from a stationary position to a pedaling action (34). Stationary ankle angle was significantly lower in relation to the three active levels, as was stationary KFA. In addition, an increase into ankle dorsiflexion and knee extension has been demonstrated at increased cycling intensity (15,18,34). As part of a PhD thesis, Bini et al. (32) compared static with dynamic measures of the lower-limb joint angles in cycling using photogrammetry of reflective markers for 3D analysis, and the Holmes method for static measurements was investigated. It was determined that ankle plantarflexion and KFA increased by 8° from static to dynamic measures. It was apparent that alterations to knee and ankle angles occur during active pedaling and that these angles alter as resistance to pedaling increases, and thus, a dynamic KFA at BDC position of 30° to 40° was previously recommended (35).

A movement into ankle dorsiflexion may increase stability around the ankle joint to transfer force effectively to the pedals to maintain the power output or increase passive tension in the muscle tendon unit to assist with force transfer. As the bicycle contact points are fixed, this increase in ankle dorsiflexion requires an increase in knee extension. Based on these findings, Bini et al. (32), Fonda et al. (36), and Farrell et al. (35) have all suggested that kinematic rather than static analysis should be used to adequately describe the lower-limb cycling motion and to optimize bicycle fit.

A more recent study assessed full-body 3D kinematics of well-trained cyclists at three different exercise intensities: 60%, 80%, and 90% of maximum heart rate (20). Ankle dorsiflexion and knee extension increased with higher intensities, while the elbow and lumbar and thoracic segments adopted a more flexed position. The mean difference in dynamic KFA from 60% to 90% intensity was 2.67°. This correlates well with the measured differences in KFA between static and dynamic knee flexion measurements which range from 5° to 8° (29). At workloads corresponding to approximately 60% of PPO, the difference between static (Holmes method) and dynamic KFA would be approximately 8° while at near maximal intensities, the progressive increase in ankle dorsiflexion would reduce this difference to approximately 5°. It is, therefore, possible to infer that optimal KFA at BDC position using dynamic measurements should range from 33° to 43° at low intensity and 30° to 40° at high intensity.

Changes in Whole Body Kinematics with Intensity

A greater ankle range of motion and forward body position has been observed at maximal workload compared with lower workloads (18). These researchers also demonstrated that athletes and nonathletes alike would move forward on the saddle during the testing, suggesting that the cyclist is intuitively seeking a more optimal position as workload increases. The above research has all been conducted using 2D sagittal plane kinematics.

An additional study by Bini et al. (19) assessed 3D kinematics and analyzed hip adduction, thigh rotation, shank rotation, pelvis inclination, and spine inclination and rotation. The main finding was a small to moderate difference in lateral spine inclination and spine rotation between recreational and competitive cyclists.

Holliday et al. (20) assessed whole body 3D kinematics at three intensities and demonstrated that ankle dorsiflexion and knee extension increased with higher intensities, while the elbow, lumbar, and thoracic segments adopted a more flexed position. There were no changes in the clinical hip and shoulder angles. This differs from previous studies that have shown hip extension increases with incremental cycling (15,16,37). The hip angles in those studies were measured as an angle from the femur, parallel to the floor, not as a clinical hip angle, as was done in this study. These previous methodologies were overly simplistic and did not take into account pelvic rotation or lumbar and thoracic spinal flexion. Thoracic lean angle changed significantly between all three intensities. This is consistent with research where there was a significant change in forward body position on the bicycle at maximal power output (18). It was suggested that cyclists increased trunk lean angle in response to muscular fatigue, and that changes in EMG preceded changes in mean trunk lean angle (38). It was hypothesized that the increase in trunk lean angle was to focus on increasing hip extensor muscle length and reducing knee flexor moment (18,38).

Holliday et al. (29) provided 3D kinematics joint angle reference values for the ankle, knee, hip, shoulder, and elbow joints measured at an intensity of 60% of peak power output for a group of 19 well-trained male cyclists. These data provide some reference points when using the Vicon marker set and provide more accurate data for the hip and shoulder joint by utilizing an additional marker placed over the T10 vertebra to quantify the effect of spine flexion on the measurement of hip and shoulder joint with greater accuracy.

There are, however, still no guidelines for clinicians and bicycle fitters for optimizing full-body kinematics in 2D and 3D for both a range of differing intensities and using different kinematic tools which utilize different anatomical marker sets. The range of systems and differing marker sets may confound this process for some time to come.

Conclusions

Numerous studies have investigated the optimal static saddle height and general consensus agrees that a static KFA of 25° to 35° using the Holmes technique is optimal for performance and injury prevention (8,12). With improvements in technology and a trend toward more dynamic assessment, research studies validating these new methods are required.

Static bicycle fitting is advantageous as it is a simple, cheaper, more reliable method (39). However, dynamic methods of assessing a cyclist's position may provide more relevant data in comparison to static methods (34). Dynamic measurements may differ depending on the cyclist's relative power output and, therefore, should to be assessed at a specific percentage of maximal heart rate or power output. This may make these assessments less reliable if the clinician does not control for the power output during analysis.

We recommend that the use of static measurements to assess other joint angles, such as the hip and shoulder angle, also should be used to guide initial position for saddle height, handlebar reach, and handlebar drop. They provide an easy, rapid, and cost-effective means of assessing the fitting that can be used in the early phases of a more complex assessment or as a standalone process for the more cost-effective and shorter assessment. Scientific reference values need to be proposed for these joints, which would allow the fitter to rapidly assess the initial position and correct gross discrepancies, before moving on to more costly, time-consuming assessment techniques to further review the position. Dynamic methods, including pressure mapping, can then be used to fine tune the bicycle configuration according to the specific needs and riding intensities of the cyclist. KFA at BDC position using dynamic measurements should range from 33° to 43° at low intensity and 30° to 40° at high intensity. Reference values and recommendations for dynamic assessments are still required for all other joints. Furthermore, intrinsic factors, such as training load and flexibility, which may affect bicycle configuration and performance, should be investigated to assess how these may influence the optimal bicycle configuration.

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