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Effects of Bicycle Saddle Height on Knee Injury Risk and Cycling Performance

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Contents

Abstract

Incorrect bicycle configuration may predispose athletes to injury and reduce their cycling performance. There is disagreement within scientific and coaching communities regarding optimal configuration of bicycles for athletes. This review summarizes literature on methods for determining bicycle saddle height and the effects of bicycle saddle height on measures of cycling performance and lower limb injury risk. Peer-reviewed journals, books, theses and conference proceedings published since 1960 were searched using MEDLINE, Scopus, ISI Web of Knowledge, EBSCO and Google Scholar databases, resulting in 62 references being reviewed. Keywords searched included 'body positioning', 'saddle', 'posture, 'cycling' and 'injury'. The review revealed that methods for determining optimal saddle height are varied and not well established, and have been based on relationships between saddle height and lower limb length (Hamley and Thomas, trochanteric length, length from ischial tuberosity to floor, LeMond, heel methods) or a reference range of knee joint flexion. There is limited information on the effects of saddle height on lower limb injury risk (lower limb kinematics, knee joint forces and moments and muscle mechanics), but more information on the effects of saddle height on cycling performance (performance time, energy expenditure/oxygen uptake, power output, pedal force application). Increasing saddle height can cause increased shortening of the vastii muscle group, but no change in hamstring length. Length and velocity of contraction in the soleus seems to be more affected by saddle height than that in the gastrocnemius. The majority of evidence suggested that a 5% change in saddle height affected knee joint kinematics by 35% and moments by 16%. Patellofemoral compressive force seems to be inversely related to saddle height but the effects on tibiofemoral forces are uncertain. Changes of less than 4% in trochanteric length do not seem to affect injury risk or performance. The main limitations from the reported studies are that different methods have been employed for determining saddle height, small sample sizes have been used, cyclists with low levels of expertise have mostly been evaluated and different outcome variables have been measured. Given that the occurrence of overuse knee joint pain is 50% in cyclists, future studies may focus on how saddle height can be optimized to improve cycling performance and reduce knee joint forces to reduce lower limb injury risk. On the basis of the conflicting evidence on the effects of saddle height changes on performance and lower limb injury risk in cycling, we suggest the saddle height may be set using the knee flexion angle method (25–30°) to reduce the risk of knee injuries and to minimize oxygen uptake.

1. Introduction

The increased popularity of cycling as a sport and recreational activity has led to a higher incidence of acute[1,2] and overuse[3,4] (90% and 85%, respectively) injuries. Anterior knee pain will occur in 25% of the population sometime during their life[5] and for cyclists, the knee joint is one of the most affected by overuse injuries.[4] Overuse injuries can be a result of poor positioning on the bicycle.[6] However, there is disagreement within scientific and coaching communities regarding optimal configuration of bicycles for athletes.[6]

The most controversial aspect of configuration of the bicycle is saddle height and, consequently, this has been the focus of most studies regarding body position on the bicycle.[7-11] Nevertheless, cyclists often select the saddle position relative to the pedals (and therefore crank) by comfort rather than scientific knowledge. There is concern that an improper position could lead to joint overuse injuries,[12] mainly those affecting the knee joint.[3] On the other hand, most of the strategies to prevent knee injuries based on the configuration of bicycle components have not been assessed by scientific research.[13]

Wishv-Roth[14] recently indicated that understanding the geometry and research around optimal configuration of the bicycle components is vital to maximize performance and minimize injury for both recreation and elite cyclists. Most guidelines reported in magazines are based on empirical data, without guidance from scientific experimental research. Sports medicine practitioners need to be able to advise their athletes on ways to reduce knee injury risk in cycling whilst maintaining or improving cycling performance. Therefore, an understanding of how saddle height may be configured and the effects it has on knee injury risk and cycling performance, are important for better prescription by the sports medicine practitioner for bicycle configuration.

This review summarizes, for the sports medicine practitioner, the literature on methods for determining bicycle saddle height configuration and the effects of saddle height on cycling performance (measured via performance time, energy expenditure/oxygen uptake [$\dot{V}O_2$], power output and pedal force application) and knee injury risk measures (measured via lower limb kinematics, knee joint forces and moments, and muscle mechanics).

2. Literature Search Methodology

Peer-reviewed journals, books, theses and conference proceedings published since 1960 were searched using MEDLINE, Scopus, ISI Web of Knowledge, EBSCO and Google Scholar databases. Keywords searched included 'body positioning', 'saddle', 'posture, 'cycling' and 'injury'. Results were searched for the keyword 'knee joint' to locate studies regarding the effects of saddle position on the knee joint. Articles were excluded if they did not have at least an English abstract, or if they were concerned with the analysis of different bicycle saddles, saddle pressure, and/or the effects on erectile dysfunction, resulting in 62 references being reviewed.

3. Findings

Section 3.1 outlines methods for configuring saddle height. Knowledge of the various methods available is needed for interpretation of the two following sections on the effects of bicycle saddle height configuration on cycling performance (section 3.2) and knee injury risk (section 3.3). Sports medicine practitioners, coaches and cyclists need to be aware of how changing seat height for performance may influence injury risk and *vice versa*.

Since initial investigations of saddle height on physiology and performance,[15] sports scientists have been searching for the 'optimal' configuration of bicycle components to increase performance and prevent injuries.[8] A variety of methods have been proposed, some of which are based upon scientific studies and others on anecdotal experience. Some methods, as in the following, are used for determining saddle height are based on lower limb length: (i) Hamley and Thomas;[15] (ii) trochanteric length;[16] (iii) length from ischial tuberosity to floor;[17] (iv) Greg LeMond;[18] and (v) the heel method.[6] A reference range of knee joint flexion has been also used to set saddle height.[18,19] Experimental studies (see table I) and reviews and empirical-based articles (see table II) examining effects of saddle configuration have shown that 'optimal' saddle height depends on the outcome variable measured as follows: (i) cycling performance time;[15] (ii) energy expenditure/ $\dot{V}O_2$;[16,17] (iii) power output;[22] (iv) lower limb kinematics;[7,11,16,20,28] (v) pedal force application;[27,28] (vi) knee joint forces and moments;[24,35] and (vii) muscle mechanics.[23,26]

3.1 Methods for Configuring Saddle Height

This section outlines the various methods for configuring saddle height. All measurements for lower leg length of the cyclist have been taken in a standing position unless otherwise indicated. For a proper configuration, the saddle height measurement must be completed with the crank in line with the seat tube and the measurement taken from the pedal surface to the top of the saddle. The use of various saddle height methods and the effects on performance or injury risk outcomes are contained in subsequent sections.

3.1.1 Percentage of Lower Leg Length Methods

The inseam leg length, ischial and trochanteric methods are all based on anthropometric length measurements of the lower leg for configuration of saddle height.

Hamley and Thomas Method

The Hamley and Thomas[15] method was probably the first research-based method. For a proper set-up using this method (see figures 1 and 2a), the saddle height must be set at 109% of inseam leg length measurement.

Trochanteric Length Method

The trochanteric length method (see figure 1) uses the length from the most prominent bony surface of the greater trochanter to the floor.[16]

Table I. Summary of experimental studies examining effects of saddle configuration

Study	Method of setting saddle height	Outcome measures	No. of subjects[a]	Main results and notes
Hamley and Thomas[15]	Percentage of inseam leg length	Time to exhaustion during constant load cycling exercise	100	109% of inseam leg minimized time to exhaustion during constant workload cycling exercise. No additional information on how different saddle heights were compared
Desipres[20]	Percentage of inseam leg length	Muscle activity and joint kinematics	3 male junior cyclists	No significant effects of saddle height (95% and 105% of the inseam leg length) on quadriceps and hamstrings activation. Ankle joint kinematics were most affected when raising the saddle height
Shennum and DeVries[17]	Percentage of inseam leg length	$\dot{V}O_2$	5 aged between 16 and 18 y	Between 100% and 103% of inseam leg length minimized $\dot{V}O_2$. Between 103% and 104% of inseam leg length could minimize power output
Rugg and Gregor[21]	Percentage of inseam leg length	Muscle estimated length, shortening velocity, moment arm of lower limb muscles	5 male cyclists	102% of the trochanteric length (high saddle height) increased shortening of the vastii group, while the hamstring group was not affected due to its bi-articular attachment
Peveler et al.[9]	Hamley and Thomas[15] method and LeMond methods[18]	Knee angle when pedal was at the bottom dead centre	14 male and 5 female cyclists	No difference between Hamley and Thomas[15] and Greg LeMond methods. Both methods did not ensure that the knee angle was between 25–30° for minimizing knee joint load
Peveler et al.[22]	Degree of knee angle, percentage of inseam leg length	Anaerobic power	9 male trained cyclists, 3 male non-cyclists, 15 female non-cyclists	25° knee angle resulted in significantly higher mean power compared with 109% inseam leg length in those that fell outside the recommended range on the anaerobic test
Peveler[8]	Degree of knee angle, percentage of inseam leg length	$\dot{V}O_2$	5 male cyclists, 2 male non-cyclists, 8 female non-cyclists	$\dot{V}O_2$ was significantly lower at a saddle height set using 25° knee angle compared with 35° knee angle or 109% of inseam leg length
Nordeen Snyder[16]	Percentage of trochanteric length	$\dot{V}O_2$, joint kinematics	10 female non-cyclists aged between 18 and 31 y	100% of trochanteric length minimized $\dot{V}O_2$ compared with 95% and 105%. Major adaptations for knee and ankle joint kinematics when shifting the saddle height
Price and Donne[11]	Percentage of trochanteric length	$\dot{V}O_2$, joint kinematics	14 competitive road cyclists with mean ± SD age of 22.9 ± 4.1 y	Reduced efficiency at 104% of trochanteric length (higher saddle height) compared with 100% and 96%. Optimal range of saddle height for minimal $\dot{V}O_2$ was between 96% and 100% of trochanteric height

Continued next page

Table I. Contd

Study	Method of setting saddle height	Outcome measures	No. of subjects[a]	Main results and notes
Jorge and Hull[23]	Percentage of trochanteric length	Muscle activity	6 cyclists of different training levels	Higher quadriceps and hamstring activation for saddle height at 95% of trochanteric length compared with 100%
Sanderson and Amoroso[7]	Percentage of trochanteric length	Muscle activity, estimated muscle length and joint kinematics	13 female cyclists with mean ± SD age of 25.6 ± 5.9 y	Increased activation of gastrocnemius medialis with greater saddle height (107%) compared with the preferred (102%) and low (92%) saddle height. Both muscles of triceps surae do not operate on the same length range when the saddle height is modified. Soleus was more affected by saddle height in relation to length and velocity of contraction than gastrocnemius medialis, mainly when the saddle height was raised by 5% of the preferred position. Gastrocnemius medialis length seems affected by the combination of ankle and knee joint kinematics
Gonzalez and Hull[24]	Percentage of trochanteric length	Average absolute hip and knee joint moments	3 male trained cyclists	97% of trochanteric length minimized the average absolute hip and knee moments
McCoy and Gregor[25]	Percentage of trochanteric length	Compressive and anterior-posterior force of the tibiofemoral joint	10 male non-athletes (mean age 29 y)	No effects of saddle height (94%, 100% and 106%) on the compressive force of the tibiofemoral joint for 10 male subjects riding at 200 W of power output and 80 rpm of pedalling cadence
Ericson et al.[26]	Percentage of the ischial tuberosity to the floor	Muscle activity	6 healthy non-cyclists aged between 20 and 31 y	Increased activation of gluteus medius, semi-membranosus, soleus and gastrocnemius medialis for 120% ischial tuberosity to the floor (higher saddle height) compared with 102% and 113%)
Ericson and Nisell[27]	Percentage of ischial tuberosity to floor	Pedal force effectiveness[b]	6 healthy non-cyclists aged between 20 and 31 y	Saddle heights (102%, 113% and 120% of the ischial tuberosity to the floor) did not affect force effectiveness
Diefenthaeler et al.[28]	1 cm relative to preferred saddle height	Pedal force, muscle activity and joint kinematics	3 elite cyclists aged between 23 and 30 y	Saddle height altered pedalling technique and muscle activity with optimal results for preferred saddle height
Rankin and Neptune[29]	Saddle position relative to the bottom bracket	Power output	Computational simulation	Small changes in saddle height (1 cm) affected power output. Ankle joint compensates for most changes in saddle height
Houtz and Fischer[30]	Lowest possible on the ergometer[c]	Muscle activity	3 healthy female non-cyclists	Reduced muscle activation in high saddle heights associated with less perceived effort

a Subjects' characteristics were not always specified in the papers. Where possible the age, sex and cycling level are reported.

b Ratio of the force perpendicular to the crank (effective force) to the total force applied to the pedal (resultant force).

c Saddle height configuration relative to subject anthropometry was not reported.

rpm = revolutions per minute; $\dot{\mathbf{V}}\mathbf{O_2}$ = oxygen uptake.

Table II. Summary of review- or empirical-based articles examining effects of saddle configuration

Study	Method of setting saddle height	Outcome measures	Paper type	Main results and notes
Burke and Pruitt[6,18]	Heel, inseam leg length and LeMond methods, and degree of knee joint angle	Optimize power output and reduce the risk of injuries	Book chapter	Knee joint range method used 25–30°. No recommendation for any of the four methods
Silberman et al.[31]	LeMond[18] and Holmes et al.[19] methods	Optimize power output and reduce the risk of injuries	Review	Greg LeMond[18] and Holmes et al.[19] methods as possibilities for saddle height configuration
Mellion[32]	Percentage of inseam leg length	Overview of overuse problems and cycling injuries	Review	109% of inseam leg to fit saddle height. 96% of the sum of shank and thigh length as an alternative set for saddle height. Saddle fore-aft adjust by the knee to pedal axis (see figure 1b)
Wanich et al.[3]	Percentage of inseam leg length	Overview of overuse problems and cycling injuries	Review	109% of inseam leg method for optimal fitting of the saddle height
Holmes et al.[19]	Degree of knee joint angle	Clinical based analysis of the common overuse problems and cycling injuries	Review	Minimal knee joint range 25–30° for minimizing knee joint load
Moore[33]	Degree of knee joint angle	Body positioning for cycling	Magazine article	Holmes et al.[19] method but with knee joint range 20–30°
Borysewicz[34]	Percentage of trochanteric length	$\dot{V}O_2$	Book chapter	Cyclists could minimize $\dot{V}O_2$ setting saddle height at 96% of trochanteric length
De Vey Mestdagh[10]	Percentage of trochanteric length or inseam leg length	Optimize power output and reduce the risk of injuries	Review	Nordeen-Snyder[16] method optimal to set the saddle height, use 100% of trochanteric length or 107% of the inseam leg
Gregor[12]	Percentage of trochanteric length or inseam leg	Biomechanical variables related to cycling	Review	Saddle height affects knee joint resultant force, muscle activity, joint kinematics and muscle length

$\dot{V}O_2$ = oxygen uptake.

Settings of 100% of trochanteric length have been reported.[11,16]

Length from Ischial Tuberosity to Floor Method

The length from the ischial tuberosity to the floor method (see figure 1) is measured with the cyclist standing and the distance taken between the most prominent bony surface of the ischial tuberosity to the floor.[17] Settings of 113% of ischial tuberosity to floor length have been reported.[35]

LeMond Method

The Greg LeMond method[18] involves the measurement of the inseam leg length and the configuration of the saddle height based on 88.3% of the distance between the top of the saddle and the centre of the bottom bracket. This method (see figures 1 and 2b) is based on the empirical experience of three-times Tour de France winner Greg LeMond. It is important to note that this method does not consider differences in the crank length dimensions. Longer crank length (i.e. 5 mm) results in lower pedalling cadence and smaller knee flexion angle.[36] Further research may look at the effects of crank length on performance variables and on variables related to the risk of injuries.

Heel Method

The empirical heel method (see figure 3a) is commonly used.[18] When the cyclist is seated on the saddle, the knee must be fully extended when the heel is on the pedal and the crank is in line with the seat tube.

3.1.2 Knee Angle Methods

Holmes et al. Method

The Holmes et al.[19] method (see figure 3b) involves measurement of the knee angle flexed when the pedal is at the bottom dead centre and the cyclist is seated on the saddle, for 25° of flexion for chondromalacea and patellar tendinitis, between 25° and 30° of flexion for quadriceps tendinitis and medial plica/medial patellofemoral ligament injury, and between 30° and 35° of flexion for iliotibial band syndrome and biceps tendinitis.

Howard Method

A variation of the Holmes et al.[19] method was reported by Burke[18] as the Howard method, for a knee angle of 30° with the pedal at the bottom dead centre and the cyclist seated on the saddle. Similar to the Holmes et al.[19] method, the knee angle measurement depends on the ankle angle. Increasing ankle plantar flexion results in higher knee flexion angle.

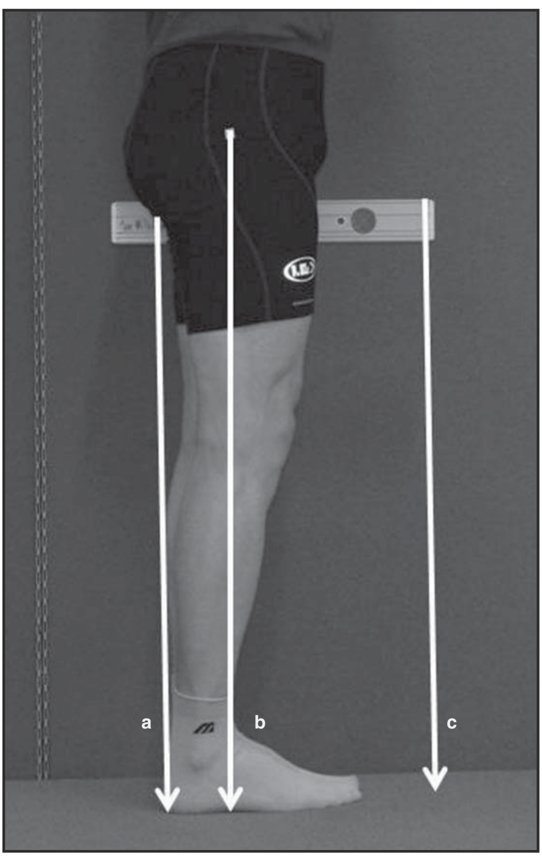

Fig. 1. Examples of lower leg length measurements: (**a**) ischial tuberosity; (**b**) trochanteric length; and (**c**) inseam leg length.

3.1.3 Comparing Methods

Peveler et al.[9] compared the knee angle when the pedal was in the bottom dead centre using different methods. They observed that length-based measures (Hamley and Thomas[15] and LeMond[18] methods) did not ensure the same knee joint angle range. Only 13 of 19 cyclists reached the desired knee angle range (25–35°) using either method. The reason is possibly because the length-based methods do not take into account individual variations in femur, tibia and foot length.[37]

Review papers by De Vey Mestdagh,[10] Silberman et al.[31] and Wanich et al.[3] reported a series of cycling posture adjustments for performance improvement and injury prevention during cycling based on measuring joint angles and segment lengths, in relation to optimal references from experimental research[15-17] and from empirical knowledge. As reported by Peveler,[8] most of the references for posture optimization on the bicycle were based on empirical data and therefore we still do not have enough valid or reliable scientific studies to determine which method is the best. The knee flexion angle method seems more reasonable than the length methods for reducing the risk of injuries and improving performance[8] because it may standardize the kinematics of the knee, which is one of the most affected joints in terms of injuries in cycling,[4] and one of the most important for power production.[24]

3.2 Effects of Bicycle Saddle Height Configuration on Cycling Performance

Since Hamley and Thomas[15] reported that bicycle saddle height affected time to exhaustion during constant workload cycling trials, studies have investigated the effect of saddle height on other parameters. In this section, we review studies that have examined the effects of saddle height on cycling performance measures (cycling performance time, energy expenditure/$\dot{V}O_2$, power output and pedal force application).

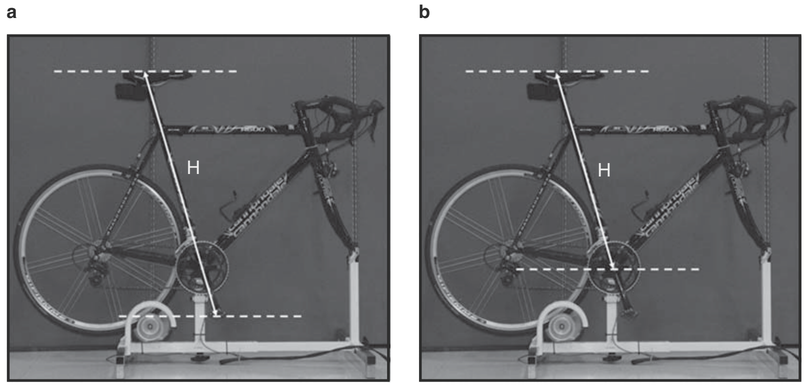

Fig. 2. Saddle-to-pedal axis distance used for (**a**) setting the saddle height by Hamley and Thomas,[15] trochanteric length,[16] and length from the ischial tuberosity to the floor[17] methods and saddle to the centre of the bottom bracket distance; and (**b**) setting the saddle height by the LeMond method.[18]

3.2.1 Cycling Performance Time

There was only one study that investigated the effects of saddle height on cycling performance time. Hamley and Thomas[15] measured time to exhaustion during constant load trials in the laboratory for 100 non-specified performers. A longer time to exhaustion could be achieved when setting the saddle height at 109% of the inseam leg length.

3.2.2 Energy Expenditure/Oxygen Uptake ($\dot{V}O_2$)

There seems to be an optimal range of saddle heights to minimize $\dot{V}O_2$ but studies differ on the optimal saddle height configuration.[15-17] Shennum and DeVries[17] and Nordeen-Snyder[16] reported that a 5% reduction in saddle height resulted in a 5% increase in $\dot{V}O_2$. $\dot{V}O_2$ was minimized with saddle height set between 100% and 103% of inseam leg length during steady-state cycling for five healthy subjects.[17] and when set to 100% of trochanteric length (about 107% of inseam leg length) for ten healthy females.[16] Borysewicz[34] reported lowest $\dot{V}O_2$ during 45 minutes of steady-state cycling when the saddle height was set at 96% of trochanteric length. $\dot{V}O_2$ during steady-state cycling has been reported as significantly lower for 25° knee angle at the bottom dead centre than for 35° knee angle at the bottom dead centre and 109% of inseam leg length conditions.[8]

3.2.3 Power Output

The effects of saddle height on power output and subsequent increased cycling performance have been observed in anaerobic exercises,[22] with suggested increased power output at higher saddle positions, compared with aerobic cycling.[11] Few studies on saddle height changes could be included for this topic because power output was set as an independent variable with focus on the measurement of physiological variables (i.e. $\dot{V}O_2$).[15-17]

3.2.4 Cycling Economy (Power Output to $\dot{V}O_2$ Ratio)

Cycling economy is an important performance predictor because it indicates the ratio between power output and $\dot{V}O_2$.[38] The majority of research on saddle height evaluated economy based on steady state cycling (i.e. fixed power output) and effects on $\dot{V}O_2$.[15-17] Peveler and Green[8,37] observed the effects of different saddle height configuration on cycling economy based on $\dot{V}O_2$ measurement during steady-state cycling, with optimal results when setting the saddle height as 25° of knee angle. Price and Donne[11] reported that with power output fixed at 200 W, economy was better with seat height at either 96% or 100% of trochanteric length compared with 104%.

3.2.5 Pedal Force Application

Any relationship between maximal performance and saddle height depends on the optimization of pedal force application.[11] Changing saddle height can affect the ankle angle,[16,22,28,29] which works as a link between the force produced in the hip and knee joints and the crank.[39,40] Ericson and Nisell[27] found no significant effects on the force transferred from the pedal to the crank generating propulsive torque for pedal forces from six recreational cyclists at different saddle heights. Pedalling technique, based on effective pedal force application of trained cyclists, compared with recreational cyclists, may be more sensitive to changes in saddle height.[27,28]

In summary, when the saddle height is set at 96–100% of the trochanteric leg length[16,17] or using the knee flexion angle (25°),[8] reduced $\dot{V}O_2$ and higher economy were observed. Moreover, when the saddle height is set to 109% of the inseam leg length ($\cong$102% of the trochanteric leg length), performance time during a time-to-exhaustion test is optimized.[15] On the other hand, no substantial effects in pedal force were found when changing the saddle height.[27]

3.3 Effects of Bicycle Saddle Height Configuration on Knee Injury Risk

One of the main reasons for the prevalence of knee injuries in cyclists is the relationship between knee joint forces and kinematics.[41] In this section are studies that have examined the effects of saddle height on knee injury risk measures (lower limb kinematics, knee joint forces and moments and muscle mechanics).

3.3.1 Lower Limb Kinematics

Most studies regarding cycling lower limb kinematics have focused on sagittal plane movement.[7,16,17] Typical ranges of motion of these joints in the sagittal plane are 45° for hip angle (from the thigh parallel to the horizontal axis), 75° for knee angle (25–100° of knee flexion angle), and 20° for ankle angle (about ±10° from the neutral ankle position).[42] Saddle height affects lower limb kinematics of the ankle,[16,20,28,29] the knee[11,12] or both the ankle and knee.[7,17] Hip and ankle joint angles are most affected by the kinematic method of measurement (i.e. 2-dimensional vs 3-dimensional [3-D]).[43] The lower limb also moves inward in the frontal plane and this movement is affected by saddle height.[44]

Between 4% and 5% change (increase or decrease) in saddle height resulted in a 25%[7] change in knee range of motion and a 40%[42] reduction in knee joint angle when the pedal was at the bottom dead centre and a 25%[11] to 51%[7] change in the maximal ankle angle. Changes in joint range of motion cause changes in muscle length[7] and in moment arms[21] of the active muscles and force production.

3.3.2 Knee Joint Forces and Moments

During stationary cycling, maximal compressive force on the patellofemoral joint has been estimated to be between 800 N (riding at 75 W

a b

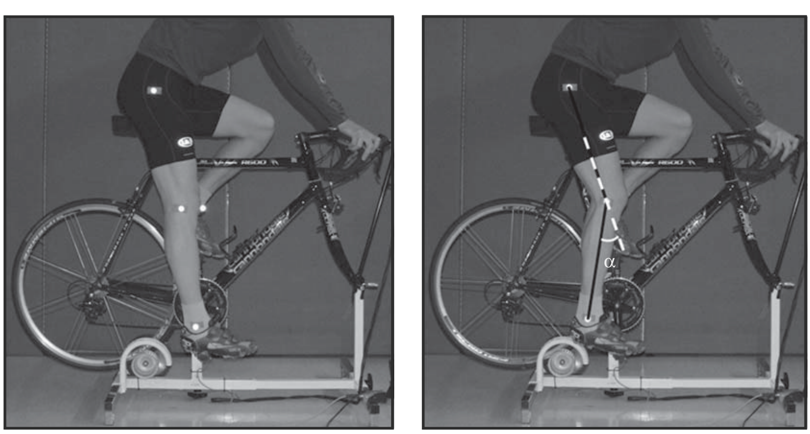

Fig. 3. Saddle height configuration based on (**a**) the heel method; and (**b**) the Holmes et al.[19] and the Howard[18] methods.

and 70 revolutions per minute [rpm]) and 1500 N (riding at 157 W and 80 rpm).[41,45,46] Assuming a contact area between the patella and the femur of 0.026 m^2[47] and a peak force of 1500 N on the patellofemoral joint,[41] we can achieve 30 MPa of pressure at the cartilage, which is above the reported physiological load.[48]

Three studies have reported compressive forces on the patellofemoral joint during cycling.[41,46,49] Ericson and Nisell[49] developed a kinetic model that estimated from trigonometric procedures the patellofemoral compressive forces during cycling. Using three saddle heights (102%, 113% and 120% from the ischial tuberosity to the floor), they showed that compressive force was inversely related to saddle height. Bressel[41] showed that backward pedalling resulted in a shift in the location of peak pedal force to a more flexed knee angle, which increased patellofemoral compressive force. Neptune and Kautz[46] described that reverse cycling has been used in rehabilitation. However, Bressel[41] reported that it can increase patellofemoral compressive force by producing higher knee flexion angles when peak force is applied on the pedal. This example highlights the relationship between joint kinematics and patellofemoral compressive load.

Neptune and Kautz's[46] muscle-skeletal model results agreed with Bressel's[41] results of increased patellofemoral compressive force during backward pedalling. However, for a very similar workload ($\cong$150 W), Neptune and Kautz[46] observed lower peak patellofemoral compressive force. This result suggested that a musculo-skeletal model improved the analysis of knee joint forces, compared with the kinetic model, because it included the effects co-contraction of the knee joint muscles. During cycling, the knee joint flexors provide an important contribution to knee extension, which could reduce the compressive patellofemoral force by co-contraction.[50]

Tibiofemoral forces are important because compressive forces on the menisci and the shear forces on the anterior and the posterior ligaments of the knee have been linked with injury.[46] Ruby et al.[44] used a 3-D kinetic model of the knee to report compressive tibiofemoral forces and anterior shear forces on the knee throughout the crank cycle. This was the first study to report medio-lateral forces on the knee and rotational moments around the long axis of the tibia, and their results led to the analysis of cycling as a 3-D movement. However, we could not find studies reporting the effects of different saddle heights on the 3-D forces and moments of the knee joint.

Ericson and Nisell[51] reported that saddle height followed an inverse relationship with tibiofemoral compressive force and shear force for six healthy subjects riding in a constant load trial. McCoy and Gregor[25] reported no effects of saddle height on the compressive force of the tibiofemoral joint for ten male subjects riding at 200 W of power output and 80 rpm of pedalling cadence. When *in vivo* forces on the anterior cruciate ligament were compared at three levels of workload (75, 125 and 175 W) and two pedalling cadences for eight subjects,[52] there were no significant differences in peak anterior cruciate ligament strain in any situation. Therefore, cycling can be useful in rehabilitation exercise programmes because of the low strain imposed on the anterior cruciate ligament. One study found that backward pedalling can increase the shear component and reduce the compressive component at the tibiofemoral joint.[46] Patients with menisci damage may be better off pedalling backwards, while patients with patellofemoral disorders or ligaments (anterior and/or posterior cruciate ligaments) injuries should avoid pedalling backwards.

The complex relationship between joints affects changes in lower limb joint moments. Increased extensor moments and reduced flexor moments were observed when saddle height was at a low position (102% of ischial tuberosity to the medial malleolus[35] or 94% of the leg length).[25] The opposite behaviour was observed with a high saddle (120% of the ischial tuberosity) compared with the average position (113% of the ischial tuberosity),[35] and for the 106% of the leg length compared with the average position (100%).[25] For the ankle joint, Sanderson and Amoroso[7] reported increased peak extensor moment with a low saddle and decreased peak extensor moment when the saddle was raised from the reference position.

Regardless of some discrepancies between studies, it seems that a 5% change in saddle height affects force production and joint moments, joint angles and muscle length. Knee joint angle and moment are strongly affected by saddle height but the optimal saddle height is still unclear because different methods have been used to measure angles and moments. Moreover, Umberger and Martin[43] and Sanderson and Amoroso[7] reported that cyclists chose an average of 104% and 102%, respectively, of the trochanteric length as the saddle height, which suggests that cyclists in these studies would have adapted to a different position than one that could minimize joint moments (97% of trochanteric length for Gonzalez and Hull[24]) or $\dot{V}O_2$.[11] As previously observed by Herzog et al.[53] and Savelberg and Meijer,[54] long-term adaptations of training can affect the muscle force-length relationship. These adaptations increase the variability of the results and make it difficult to assess the contribution of adapted position. Only Umberger and Martin[43] and Sanderson and Amoroso[7] reported the preferred saddle heights of their cyclists.

Few studies have estimated knee joint forces during cycling with changes in saddle height, and some controversial results have emerged from the reviewed research.[25,51] For the patellofemoral joint, an inverse relationship was observed in one study[49] while for the tibiofemoral joint, controversial results have been reported.[25,51] Joint kinematics and moments results have had different outcomes.[11,16,20,28] Joint kinematics and moments also seem to depend on cycling expertise, which compromises comparison between studies.[11,16,20,28] Therefore, we do not have enough evidence to define 'optimal' saddle height based on the results of knee joint forces or joint kinematics. If the aim is to minimize the risk of patellofemoral joint injuries, the inverse relationship between saddle height and patellofemoral compressive force may be used as a reference.

3.3.3 Muscle Mechanics and Activation Patterns

The effects of muscle length on force production have been a focus of much sports science research.[55] Direct measurement of muscle length is usually not possible for ethical reasons, but indirect measurements using ultrasound,[56,57] or anthropometric models[58] have been used to estimate fascicle length and its effect on force production in sports.[59] Grieve et al.[58] proposed anthropometric methods based on cadaver measurements of the muscle-tendon unit length while Frigo and Pedotti[60] reported a model to estimate muscle-tendon unit length based on the line of action of lower limb muscles. Both studies reported relationships between predicted muscle length and kinematics, which allow the estimation of muscle length during dynamic situations.

Some studies[7,21,59] have proposed measuring kinematics to infer muscle length during cycling. The force production and the magnitude of joint load depend on muscle length. Rugg and Gregor[21] observed in five cyclists pedalling at 90 rpm of cadence that increasing saddle height resulted in increased shortening of the vastii group, but no significant change in the hamstring group, possibly due to its bi-articulate attachment. Sanderson and Amoroso[7] applied the model of Grieve et al.[58] to evaluate the effects of three different saddle heights on gastrocnemius and soleus. Gastrocnemius and soleus muscles operated in different length ranges when saddle height was raised 5% and lowered 10% from the preferred saddle height. Length and velocity of contraction in the soleus was more affected by saddle height than that in the gastrocnemius, with greatest changes occurring when the saddle height was raised 5% from the preferred position. Gastrocnemius length seemed to be affected by the combination of ankle and knee joint kinematics. These results extend previous data with similar experimental design.[12]

There is inconclusive information on muscle-length behaviour during dynamic situations.[56] Computational models have been used to estimate muscle force production and length of shortening during cycling,[61,62] but these models have not been used to investigate saddle height changes. Future simulations of muscle-length force production during cycling at different saddle heights would add important information regarding the best saddle height for muscle force production.

Given the changes in muscle length that occur with changes in saddle height, it is likely that neural drive to control muscle force would also change. Muscle force and joint load also depends on neural drive. The first report of changes in muscle activation at different saddle heights was by Houtz and Fischer,[30] who observed increased muscle activation when the saddle was reduced 15% from the reference position. Houtz and Fischer's study,[30] and later studies,[20,28] have been conducted with a limited numbers of subjects, which does not allow results to be generalized to the population. Jorge and Hull[23] found increased quadricep and hamstring activation with saddle height set at 95% of trochanteric length compared with 100%. For high saddle height based on the ischial tuberosity to floor height, Ericson et al.[26] found that the semi-membranosus and gastrocnemius medialis had increased activation for six healthy subjects, which was subsequently confirmed by Sanderson and Amoroso[7] for 13 trained female cyclists. The differences may be related to the preparation of surface electromyography or to the pedalling skills of the subjects (i.e. trained cyclists or healthy subjects). There was also a report that muscle timing (i.e. onset and offset) would be modified by saddle height;[12] however, there is still no conclusive evidence. Currently, we cannot define an optimal saddle height for improving performance or preventing injuries using evidence from muscle activity studies.

3.4 Limitations of the Cited Studies

There are many limitations in the research studies reviewed. The different approaches for setting saddle height made it difficult to compare results between studies. Only Shennum and DeVries[17] reported their results of $\dot{V}O_2$ with comparison to other methods, while Peveler et al.[9] highlighted the differences in the knee joint angle using different methods to configure the saddle height.

Sample size ranged from 3[30] to 100.[15] Expertise of the subjects ranged from trained road cyclists[11] to healthy non-cyclists[16,17,26,27] to mixed levels of cycling experience.[8] It is possible that experienced cyclists adapt to a specific position as a result of the time spent training. Such adaptation may be less marked for recreational cyclists or those that ride in multiple positions (e.g. triathletes). However, we could not find any studies that had a focus on training cyclists to ride at different saddle heights and measured the differences in performance.

Different outcome variables were analysed to indicate the effects of optimal saddle height for injury prevention and performance optimization. Most studies did not report the sensitivity or variability of these variables to changes in saddle height. It is possible that different positions are optimal for performance versus injury prevention. The magnitude of the differences in some studies[8,37] was too small (effects sizes 0.07–0.20), so it was unclear how substantial the changes were in the studies.

If we consider previously reported optimal settings for saddle height (96–100% of trochanteric length) and we use the 'optimal' setting of the saddle to the bottom bracket length (0.773 m) and crank length (0.191 m) reported by Gonzalez and Hull,[24] (resulting in a saddle height of 0.964 m) for a subject 177.8 cm tall, cycling at 90 rpm, our 'optimal range' for the saddle height will be between $\cong$0.925 m and 0.964 m. This difference of $\cong$4 cm is more than any experienced cyclist would consider, and a 4% difference in saddle height would result in ~5% change in $\dot{V}O_2$.[16]

Most methods of setting saddle height resulted in different joint kinematics, which would affect joint forces and increase risk of injury.[9]

3.5 Practical Implications and Recommendations

The configuration of the bicycle saddle height is not standardized in relation to the methods that can be used for this configuration. The optimal reference for each method is not well defined and a wide range (i.e. 96–100% of the trochanteric length to the floor) used for performance optimization has been proposed. Evidence for performance improvements has led to using the knee joint angle method from Holmes et al.[19] rather than the leg length methods.[8] Future studies may focus on the effects of previous training adaptation on the optimal reference for the knee angle for setting the bicycle saddle height.

Given the limitations of the research studies reviewed, sports medicine practitioners are encouraged to advise their cycling athletes to configure their bicycle using the Holmes et al.[19] method, which involves the measurement of the knee angle when the pedal is at the bottom dead centre. For proper configuration of the saddle height using this method, the knee must be flexed between 25° and 30°, which has been related to lowering the knee joint load[10] and improving cycling economy.[8]

4. Conclusions

Methods for determining optimal saddle height are varied and have not been comprehensively compared using experimental research studies. There is limited information on the effects of saddle height on lower limb injury risk, but more information on the effects of saddle height and cycling performance. The range of 25–30° of knee flexion has been advocated to reduce the risk of knee injuries and minimize $\dot{V}O_2$. Given that overuse knee joint injury is common in cyclists, future studies should determine how saddle height can be optimized to improve cycling performance and reduce knee joint forces to reduce lower limb injury risk.

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