

Summer 2019

Effect of Pedal Stance Width Manipulation via Pedal Spacers on Lower Limb Frontal Plane Kinematics During Cycling

Andrew Fife

Western Washington University, andrewfif@gmail.com

Follow this and additional works at: <https://cedar.wvu.edu/wwuet>



Part of the [Kinesiology Commons](#)

Recommended Citation

Fife, Andrew, "Effect of Pedal Stance Width Manipulation via Pedal Spacers on Lower Limb Frontal Plane Kinematics During Cycling" (2019). *WWU Graduate School Collection*. 893.

<https://cedar.wvu.edu/wwuet/893>

This Masters Thesis is brought to you for free and open access by the WWU Graduate and Undergraduate Scholarship at Western CEDAR. It has been accepted for inclusion in WWU Graduate School Collection by an authorized administrator of Western CEDAR. For more information, please contact westerncedar@wwu.edu.

**EFFECT OF PEDAL STANCE WIDTH MANIPULATION VIA PEDAL
SPACERS ON LOWER LIMB FRONTAL PLANE KINEMATICS DURING
CYCLING**

By

Andrew Fife

Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

ADVISORY COMMITTEE

Dr. Harsh Buddhadev, Chair

Dr. Jun San Juan

Dr. Sarah Paxson

Dr. Dave Suprak

GRADUATE SCHOOL

David L. Patrick, Interim Dean

Master's Thesis

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Western Washington University, I grant to Western Washington University the non-exclusive royalty-free right to archive, reproduce, distribute, and display the thesis in any and all forms, including electronic format, via any digital library mechanisms maintained by WWU.

I represent and warrant this is my original work, and does not infringe or violate any rights of others. I warrant that I have obtained written permissions from the owner of any third party copyrighted material included in these files.

I acknowledge that I retain ownership rights to the copyright of this work, including but not limited to the right to use all or part of this work in future works, such as articles or books.

Library users are granted permission for individual, research and non-commercial reproduction of this work for educational purposes only. Any further digital posting of this document requires specific permission from the author.

Any copying or publication of this thesis for commercial purposes, or for financial gain, is not allowed without my written permission

Andrew Fife

8/4/2019

**Effect of pedal stance width manipulation via pedal spacers on lower limb frontal plane
kinematics during cycling**

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Andrew Fife
August 2019

Abstract

Anecdotal evidence suggests that frontal plane kinematics of the lower extremity may be an important aspect of bicycle fit, however, frontal plane adjustments are often overlooked during common fit procedures. The purpose of this study was to manipulate pedal stance width through the use of pedal spacers to determine their influence on frontal plane kinematics of the hip, knee, and ankle during cycling. Twenty-four young healthy subjects (12 female) recreational cyclists completed five minutes of pedaling at their preferred cadence and power output under three stance widths conditions: no spacer, 20 mm spacer, and 30 mm spacer. The pedaling cadence and power output were kept identical for all experimental conditions. Lower extremity marker position data were captured at 250 Hz for the last two minutes of each condition. Sixty consecutive crank cycles were analyzed to identify peak hip, knee, and ankle angles in the frontal plane. With an increase in pedal stance width, hip and knee peak abduction angles increased and peak adduction angles reduced ($p < .05$). The ankle joint position was not affected by the stance width conditions. Pedal spacers are an effective way of manipulating pedal stance width and frontal plane kinematics of the lower extremity.

Keywords: knee adduction, bicycle fit

Acknowledgments

I would like to thank Western Washington University for the opportunity to conduct this research. I would like to express thanks to Dr. Harsh Buddhadev as my thesis chair and mentor. His guidance and encouragement were necessary for my success during this research. Dr. Buddhadev is very patient, focused, and has energy for his position that I intend to emulate throughout my academic career. I thank my committee members for their attention to detail and contribution to strengthening my research and writing. I especially appreciate the involvement of Dr. Sarah Paxson, and her flexibility to accommodate my schedule even when inconvenient.

I appreciate all of the support and expertise of those involved in the research as well as those that helped me consider the experiment from different points of view such as Dr. Lorrie Brilla. I am grateful for my research assistant, Danica Fife, for her contribution and diligence in the data collections. Her willingness to attend and assist in the collections was amazing. Her support and encouragement as my wife was especially motivating.

Lastly, nearly every subject came from referrals. I would like to thank the participants that were willing to introduce me to their friends and teammates in order to collect data for the experiment. The donation of their time without any tangible reward was gracious and thoughtful. Without their effort, recruiting subjects would have been far more challenging.

Table of Contents

Abstract.....	iv
Acknowledgements.....	v
List of Tables and Figures.....	viii
List of Appendices.....	ix
Chapter I: Manuscript.....	1
Introduction.....	1
Methodology.....	2
Participants.....	2
Data collection.....	3
Data analysis.....	5
Statistical Analysis.....	5
Results.....	6
Discussion.....	11
Chapter II: Review of Pertinent Literature.....	14
Introduction.....	14
Bicycle Fit.....	15
Seat height and knee angle.....	17

Handlebar position and trunk angle.....	21
Normal 3-D kinematics.....	21
Relevant sagittal plane kinematics.....	21
Frontal plane kinematics.....	26
Decreasing injury through bicycle fit.....	28
General methods.....	28
Manipulation of stance width.....	30
Pedal spacers.....	32
Anecdotal evidence of efficacy.....	33
Summary.....	34
References.....	35
Appendices.....	43-50

List of Tables and Figures

Table 1. Lower extremity frontal plane kinematics.....	9
Figure 1. Ensemble frontal plane joint angles.....	10
Figure 2. Ways to adjust a bicycle during fit.....	16
Figure 3. Knee over pedal spindle during fit.....	20
Figure 4. Seat height at bottom dead center during fit.....	23
Figure 5. Sagittal plane relative joint angles.....	24
Figure 6. Sagittal plane traces of lower extremity	25
Figure 7. Knee adduction traces during cycling.....	27
Figure 8. Foot-shoe-pedal interface.....	29
Figure 9. Different sizes of pedal spindle.....	31
Figure 10. Kneesavers pedal spacers.....	32

List of Appendices

Appendix A: Informed Consent.....	43
Appendix B: Table of Sagittal Plane Kinematic data of the Lower Extremity.....	46
Appendix C: Journal of Applied Biomechanics Author Guidelines.....	47

Chapter I

Introduction

Cycling is a common activity used during rehabilitation in a variety of clinical settings as well as for fitness and recreation.^{1,2,3,4,5} A bicycle fit is performed with the goal to optimize the rider's posture to enhance performance, reduce incidence of injury, and increase comfort.^{6,7,8,9,10} Bicycle fits commonly include manipulations of the handlebars, seat height, and saddle fore-aft position.⁶ These adjustments are generally used to optimize trunk angle and knee joint range of motion (ROM).^{11,12}

Cycling motion of the lower extremity primarily occurs in sagittal plane. Hence, joint motion in this plane has been studied extensively^{7,12,13,14} and when performing a bike fit, focus has traditionally involved manipulations in the sagittal plane.^{6,15} Previous research has recommended certain bike fit criteria (i.e., certain joint positions and ROM) to optimize rider posture for performance and increased comfort.¹² These common bike fit criteria include a trunk angle of 45°, when hands are placed on top of the handlebars,^{6,12,16} and knee flexion angle of 30° at the bottom dead center (BDC) of a crank cycle.^{8,12,15,17,18}

Range of motion at the lower extremity joints in the frontal plane during the bike fit is under-researched and often overlooked. Knee abduction and adduction angles have been recently suggested to be important aspects of bike fit^{1,19} as changes in frontal plane motion at this joint influence comfort at the knee joint during cycling.^{20,21} For example, individuals with medial compartment knee osteoarthritis demonstrate a varus deformity at the knee joint^{2,22} and this posture increases compressive forces on the medial side of the knee joint. For these individuals with knee osteoarthritis, a strategy to reduce the varus posture at the knee involves walking with

wider stance width, which has shown to improve comfort and favorably change frontal plane joint motion acutely.^{2,23}

An effective and convenient method to manipulate stance width on a cycle ergometer is through the use of pedal spacers.²⁴ Pedal spacers are machined components that insert between the crankset and the pedal. Interfacing pedal spacers between the pedal and crank effectively increases pedal stance width and thus could favorably influence frontal plane knee joint motion and postural alignment (i.e., reduce knee adduction angles). Pedal spacers can be purchased in multiple lengths to manipulate stance width on a cycle ergometer to different extents. Currently, there are several pedal spacer options available commercially with claims that these pedal spacers could make a favorable change in frontal plane knee position during cycling; however, there is no research supporting claims of favorable changes to knee joint motion in the frontal plane.

There is a need to show the feasibility of changing knee joint frontal plane motion through the use of pedal spacers in young healthy adults during cycling before such research is conducted on individuals with medial compartment knee osteoarthritis. Therefore, the purpose of this study was to examine the effect of pedal stance manipulation, via different lengths of pedal spacers, on lower extremity frontal plane joint motion in healthy young adults. We hypothesized that: 1) the peak knee adduction angle would decrease with increased stance width (i.e., spacers; 20 mm and 30 mm) compared to no spacer stance width, and; 2) peak knee adduction angles would be lower for longer spacer condition (30 mm) compared to the shorter spacer condition (20 mm).

Methods

Participants: Twelve female (Mean (SD): 24.5 (3.7) years; 167.4 (5.0) cm; 60.8 (6.9) kg)

and 12 male (22.3 (3.5) years; 183.8 (7.0) cm; 84.2 (15.7) kg) participants were recruited from the campus of Western Washington University and the local community. The appropriate sample size was determined using G*Power 3.1 software.^{25,26} A sample size of 24 participants was needed to achieve a statistical power of 0.8 to detect a medium effect size main effect (Cohen's $f = 0.25$) of pedal spacers on lower extremity joint angles at an alpha level of 0.05. Recreational cyclists were classified as people they self-reported that they had ridden a bicycle for recreation, transportation, and/or exercise throughout the majority of the past year.^{27,28,29} Participants with pain or recent injuries to the lower extremity were excluded.^{2,23,30} The Western Washington University Institutional Review Board approved the study design and procedures and all subjects provided an informed consent document.

Data Collection: Each participant completed one testing session that lasted approximately 60 minutes. Prior to the arrival of the participants, the capture volume for a six-camera Vicon system (Vicon Vero, Centennial, CO, USA) was calibrated and the calibration error always remained under 0.5 mm.³¹ All cycling tests were carried out on a Velotron Dynafit ergometer (Racer-Mate Inc, Seattle, WA), which allowed for seat and handlebar position adjustment as well as the ability to control power output as cadence varied. The cycle ergometer was also calibrated prior to all data collection sessions by executing the Accuwatt calibration check test (Racer-Mate, Inc, Seattle, WA).^{27,32} The ergometer calibration deviated no more than 0.5% from the factory settings across all data collection sessions.

Participants completed the informed consent and a health history and cycling experience questionnaire upon arrival to determine if they met the inclusion and exclusion criteria for the study.^{23,27} Each participant was provided with lycra cycling shorts, a tank top, and appropriately sized cycling shoes (Giro, Santa Cruz, CA) that clipped into the pedals (Shimano, Sakai, Japan).

Twenty-four retroreflective 14 mm markers were placed on both lower extremities using a modified lower extremity Plug-in Gait model from Vicon. The modification to the model included adding 2 markers each to the pelvis, thigh, shank, and foot segments to recreate markers that were likely to be covered as the participants adopted a cycling posture and to identify individual crank cycles. Using the Vicon motion capture system, marker position data were captured at a sampling frequency of 250 Hz. Static trials were collected with participants standing in motorcycle pose according to the plug-in gait guidelines.³³

A cycling ergometer fit procedure was implemented next in order to standardize the cycling posture of the participants and minimize effects observed due to influences other than manipulations in pedal stance width.^{27,30,34} A handheld goniometer was used to determine all static angles. Seat height was set with the crank positioned at bottom dead center and the knee flexed to 30°. ^{6,7,8,35,36} Seat fore-aft position was set so the pole of the patella was located directly superior to the pedal axle in the sagittal plane when the crank was forward and parallel to the ground.^{27,37,38} Finally, handlebar position was adjusted to achieve a trunk angle of 30° from the vertical plane to make cycling more comfortable. ^{6,12,15,27} Participants then performed a 5-minute warm-up and familiarization on the ergometer at their self-selected power and cadence. This familiarization also served to determine the preferred power output and cadence of the participants, which was used for the three experimental conditions. The pedal stance width of the no-spacer condition was 262.8 mm wide from pedal center to pedal center as per manufacturer specifications, which was confirmed with digital calipers (Vinca, Clockwise tools, CA).

Each participant performed three experimental stance width conditions (no pedal spacers, 20 mm pedal spacers, and 30 mm pedal spacers), with the order of completion randomly assigned. Subjects completed each condition by pedaling at their preferred power output and

cadence (determined in the familiarization session) for five minutes. The preferred power outputs and cadences for female and male participants were 91.1 (31.4) Watts (W) and 73.5 (12.3) revolutions per minute (rpm) and 120.7 (34.5) W and 69.8 (7.8) rpm, respectively. Marker position data during the experimental conditions were captured during the last two minutes of the five minutes of each condition.^{7,14} A 3-5-minute rest interval separated the conditions during which the pedals were prepared for the subsequent condition. After each fitting, the pedals were tightened to a torque of 45 Nm with a calibrated torque wrench based on the manufacturer guidelines.³⁹

Data analysis: Marker position data were filtered at 4 Hz using a 4th order Butterworth filter.^{26,27,40, 41,42} The dynamic plug-in gait pipeline was executed to determine the frontal plane hip, knee, and ankle joint angles.³³ Top dead centers (TDC) of individual crank cycles were identified using markers positioned on the feet in close proximity to the left and right pedal spindles. Using the computed TDC positions, joint angle data for 60 consecutive crank cycles were identified to attain stable kinematic data. For each crank cycle, peak and minimum values were determined for hip, knee, and ankle frontal plane angles and averaged across 60 cycles for the statistical analysis.

Statistical analysis: First, two-way (sex x condition) mixed model analysis of variance (ANOVA) with repeated measures were performed to determine the effects of sex and condition on the dependent variables. If no such differences existed, then one-way ANOVAs with repeated measures were used to evaluate the effects of stance width manipulation via pedal spacers (3) on the frontal plane hip, knee, and ankle peak and minimum angles. Alpha level was set a priori at 0.05. A Greenhouse-Geisser correction was performed if the assumption of sphericity was violated. For significant main effect of condition and sex-condition interaction, post-hoc analyses

were performed with t-tests. Effect size was calculated as partial eta squared (η_p^2). Partial eta squared was interpreted using guidelines provided by Vincent where, $\eta_p^2 > 0.01$ was small, $\eta_p^2 > 0.06$ was medium, and $\eta_p^2 > 0.15$ was large.⁴³ Statistical analyses were conducted using SPSS (version 21; IBM Corporation, Armonk, NY).

Results

Hip frontal plane motion

For the hip frontal plane motion, the thigh remained in an abducted position throughout the crank cycle. The hip position at TDC had a small magnitude of abduction and moved towards adduction during the first 60° of the crank cycle. It then moved toward an abducted position at BDC before returning to a less abducted position at TDC (figure 1; right panel).

For hip frontal plane ROM, there was a sex-condition interaction ($F_{2,44}=3.269$; $p=.047$; $\eta_p^2=.129$; Table 1). Post-hoc comparisons showed that there were no differences in male and female participants' hip frontal ROM for any of the conditions. In addition, for male participants there was no change in frontal ROM across the conditions. However, for female participants there was a 0.4° difference in hip ROM between no spacer and 20 mm spacer condition for female participants ($p = .040$). For maximum and minimum hip adduction angles, there was no sex-condition interaction or a sex main effect ($p > .05$). There was a significant main effect of condition. Hip frontal plane minimum ($F_{2,44}=46.068$; $p<.001$; $\eta_p^2=.677$) and maximum ($F_{2,44}=36.271$; $p<.001$; $\eta_p^2=.622$) values became systematically more abducted as pedal stance width increased from the no spacer condition to 20 mm and 30 mm spacer conditions. The magnitude of this shift in frontal plane peak values ranged from 1.4-1.6 °.

Knee frontal plane motion

For knee frontal plane motion, the shank moved from an adducted position at TDC to an abducted position at BDC and then returned to an adducted position when the crank cycle was completed (figure 1, middle panel). There were no sex-condition interactions for the knee frontal plane peak values or ROM ($p > .05$). However, there were a significant main effect of sex for both peak and minimum knee adduction values. For male participants, the peak adduction angle was 8.5° more than females ($F_{1,22} = 10.548$; $p = .004$; $\eta_p^2 = .324$). Conversely, the female peak knee abduction angle was 5.8° more than males ($F_{1,22} = 6.241$; $p = .020$; $\eta_p^2 = .224$). There was also a significant main effect of condition for peak knee frontal plane values ($F_{2,44} = 20.786$; $p < .001$; $\eta_p^2 = .486$). Similar to hip motion, the shank position became systematically less adducted as pedal stance width increased from no spacer condition to 20 mm ($p = .003$) and 30 mm ($p < .001$) spacer conditions. The magnitude of decrease in the peak knee adduction values across conditions ranged from 1.1 - 2.1° . There was also a reduction in knee adduction angle from 20 mm to 30 mm spacer conditions ($p = .012$). Conversely, knee abduction angles increased with increase in pedaling stance width ($F_{2,44} = 19.261$; $p < .001$; $\eta_p^2 = .467$). Compared to the no spacer condition, the magnitude of peak knee abduction values were 1.2° greater for the 20 mm spacer ($p = .002$) and 1.8° greater for the 30 mm spacer conditions ($p < .001$). With increase in stance width from 20 mm to 30 mm spacer condition, the magnitude of peak knee abduction increased 0.5° , but this difference was not statistically significant ($p = .078$).

Ankle frontal plane motion

The foot remained in a slightly inverted position throughout the crank cycle (figure 1, left panel). There was no effect of sex or pedal spacer conditions on the frontal plane ankle peak and minimum angles. For the ankle frontal plane ROM, a sex main effect was observed ($F_{1,22} = 7.191$; $p = .014$; $\eta_p^2 = .246$). The feet of female participants were slightly more adducted ($\sim 0.6^\circ$) compared than male participants. A condition main effect was also observed for ankle frontal plane ROM ($F_{2,44} = 4.254$; $p = .020$; $\eta_p^2 = .162$). Compared to the no spacer condition, the 30 mm spacer condition was 0.062° more everted ($p = .020$). Also, 30 mm spacer was 0.062° more everted ($p = .011$) than the 20 mm spacer conditions.

Table 1. Effect of stance width condition on lower extremity frontal plane joint kinematics

	Female			Male		
	No spacer	20 mm spacer	30 mm spacer	No spacer	20 mm spacer	30 mm spacer
Maximum Hip adduction (°) *	-7.8 (2.8)	-8.7 (2.3)	-9.5 (2.5)	-8.1 (4.1)	-8.9 (4.3)	-9.3 (4.2)
Minimum Hip Adduction (°) *	-3.4 (2.9)	-4.7 (2.7)	-5.2 (3.0)	-4.5 (4.2)	-5.1 (3.9)	-5.9 (3.9)
Hip Frontal ROM (°) ^	4.5 (1.3)	4.0 (1.2)	4.3 (1.6)	3.6 (1.3)	3.8 (1.5)	3.4 (1.4)
Maximum Knee Adduction (°) #, *	1.7 (5.6)	0.3 (6.1)	-0.4 (5.9)	9.9 (6.7)	9.2 (7.8)	7.9 (6.3)
Minimum Knee Adduction (°) #, *	-4.7 (6.1)	-6.3 (6.8)	-6.8 (7.0)	0.6 (4.2)	-0.3 (5.2)	-0.8 (4.1)
Knee Frontal ROM (°)	6.3 (2.4)	6.5 (2.4)	6.5 (2.4)	9.4 (4.9)	9.5 (4.9)	8.6 (4.8)
Maximum Ankle Inversion (°)	2.6 (1.8)	2.5 (1.9)	2.5 (1.9)	1.8 (1.5)	1.7 (1.6)	1.8 (1.5)
Minimum Ankle Inversion (°)	1.0 (1.9)	0.9 (1.9)	0.9 (2.0)	0.7 (1.7)	0.7 (1.8)	0.8 (1.7)
Ankle Frontal ROM (°) #, *	1.6 (0.6)	1.6 (0.5)	1.6 (0.6)	1.1 (0.5)	1.1 (0.5)	1.0 (0.4)

* Values are Mean (SD); negative values are abduction and positive values are adduction; * statistically significant condition main effect; # statistically significant sex main effect; ^ statistically significant sex-condition interaction.

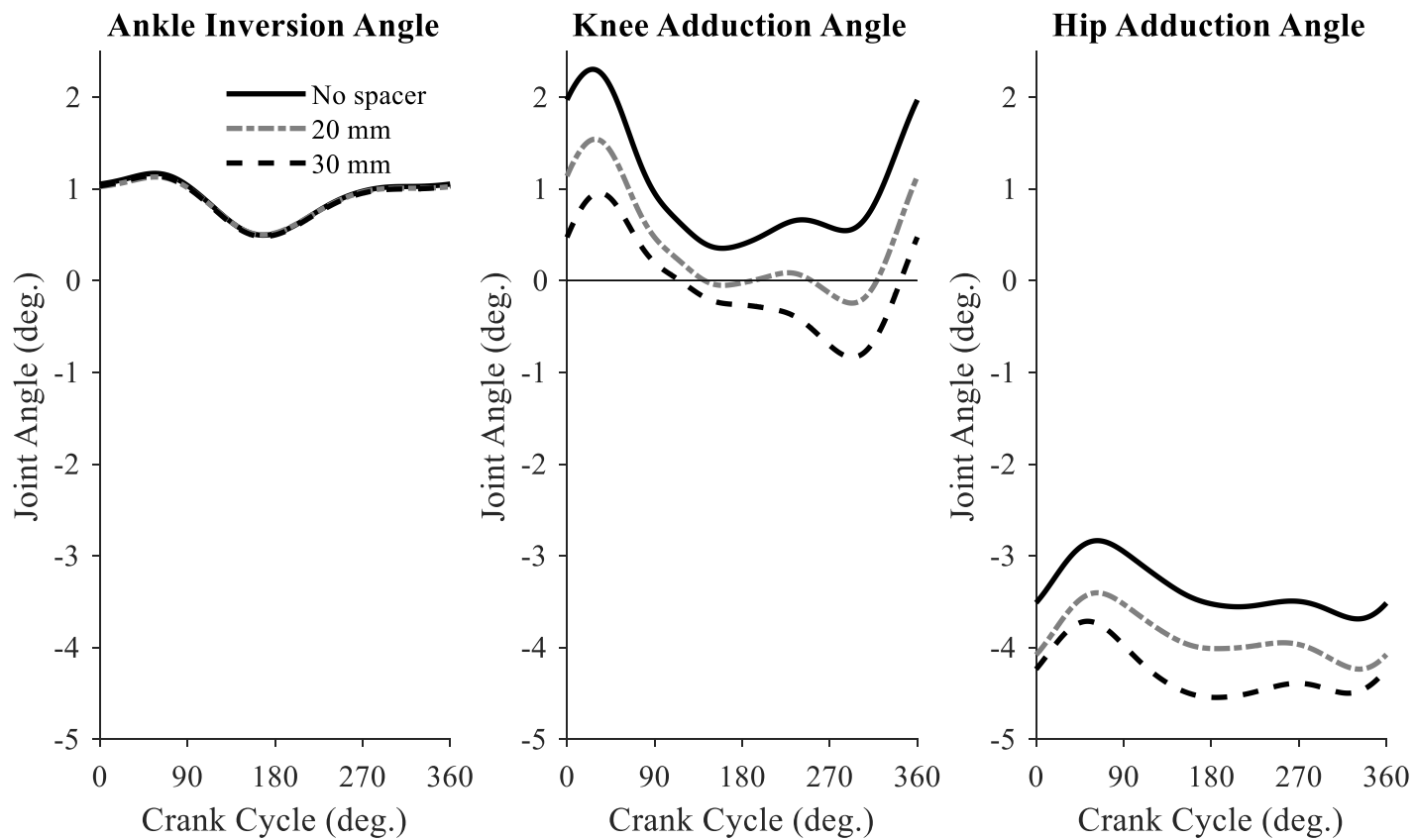


Figure 1. Frontal plane joint angles ensembled over 60 consecutive crank cycles for all participants (male and female). Positive values represent ankle inversion and knee and hip adduction. Negative values represent ankle eversion and knee and hip abduction.

Discussion

The purpose of this study was to examine the effect of pedal stance manipulation, via different lengths of pedal spacers, on lower extremity frontal plane joint motion in healthy young adults. Our hypotheses were that: 1) peak knee adduction angles would be lesser for the increased stance width conditions (i.e., spacers; 20 mm and 30 mm) compared to no spacer traditional stance width, and; 2) peak knee adduction angles would be lower for larger spacer condition (30 mm) compared to the shorter spacer condition (20 mm). The data support both of these hypotheses. Peak knee adduction angle was significantly decreased with increases in pedal stance width (peak knee adduction angle: no spacer > 20 mm spacer > 30 mm spacer; Table 1). These differences had large effect sizes but were small in magnitude (in degrees).

The data demonstrated that overall the lower extremity moved into a more abducted position with increase in pedal stance width. Because the feet were clipped into the pedals, there was little to no change in position or ROM of the feet at the ankle joint across the stance width conditions.^{21,44,45} The majority of the increases in the lower extremity abduction positions were observed at the hip and knee joints. When the data were examined together for both sexes, the magnitude of increase in the hip abduction angle was 1.4-1.6 °. Although this change does not appear to be large, compared to the no spacer condition, these were 20% greater for the 20 mm spacer condition and 40% greater for the 30 mm spacer condition. Similarly, the knee adduction angle decreased with the stance width conditions by 1.1-2.1 °. Compared to the no spacer condition, the knee was 18 % and 36 % less adducted during the 20 mm and 30 mm spacer conditions, respectively. Overall, these changes appear to be very subtle in overall angle magnitude, but they account for a large percent change in peak values.^{14,24,46} To the authors' knowledge, this is the

first study to systematically examine lower extremity frontal plane joint positions and ROM for cycling at different stance widths.

The frontal plane joint ROM data showed that pedal spacer conditions affected the knee joint ROM most, followed by the hip and the ankle joint ROM. This hierarchy of effect on lower extremity joint ROM is understandable because the feet are fixed at the pedals and the proximal ends of the thighs are semi-fixed at the seat.⁴⁵ The knees are the least constrained joints during the pedaling motion, which perhaps explains the relatively larger effect on the frontal plane ROM at this joint. Indeed, the largest increase in joint abduction position (in degrees) with increased stance width was also in the same order; the largest change in peak angles occurred at the knee followed by the hip. The frontal plane joint angle data for the no spacer condition observed in the current study are comparable to data reported previously.^{26,41,44} In the current study, hip abduction peak values ranged from 4° to 8° which are comparable to 2° to 8° reported by Umberger and Martin.⁴⁴ The knee frontal plane peak values in the current study ranged from 6° of adduction to 2° of abduction with a frontal plane ROM of 8°. Previous research reported similar peak values with ROM ranging between 10-12°. ^{26,41,44} In the current study, the participants' feet were clipped into the pedals and therefore, ankle frontal ROM was under 2°, which was slightly lower than other studies (3-6°). ^{26,44}

The pedal spacers are speculated to influence frontal plane knee joint posture which could reduce knee pain in individuals such as those with knee osteoarthritis.^{47,48,49} The data from the current study show that pedal spacers subtly affect frontal plane knee angles systematically with increases in pedal stance width. Although the changes in frontal plane joint angle data are subtle, all of the participants self-reported that pedaling at each specific stance width condition felt distinct from one another. To elucidate the effect of stance width on frontal plane knee joint

mechanics and to determine its influence on knee comfort, future researchers should consider examining 3-D reaction forces and frontal plane knee joint kinetics.

The focus of the current study was primarily to examine the effect of different pedal stance width conditions, manipulated via pedal spacers, on frontal plane kinematics during cycling. To allow for our data to be generalizable to both sexes, we recruited young male and female participants.^{2,26,30,44} The male participants' shank was more relatively adducted at the knee compared to female participants throughout the crank cycle. The stance width conditions systematically affected frontal plane kinematics at the knee joint for both the sexes in a similar manner. Our data show that frontal plane knee joint angles differ based on sexes and therefore, when increasing stance width, the natural knee joint position of an individual should be taken into account. For example, adult males whose knees are in a relatively more adducted position during cycling could benefit from increasing stance width.

In conclusion, stance width condition systematically affected frontal plane knee joint position. Compared to the no spacer condition, the knee angle was less adducted for the 20 mm and 30 mm spacer conditions. In addition, the knee was less adducted for the 30 mm compared to the 20 mm spacer condition.

Chapter II

Review of literature

The modern bicycle is used commonly for transportation, exercise, and outdoor recreation.^{50,51,52} Benefits of cycling are accessible to both young people and older adults and have been well documented.^{53,54,55} Benefits of cycling include improved VO_{2max} , decreases in all-cause cardiovascular disease and coronary heart disease, as well as reductions in obesity and other metabolic diseases.^{56,57,58} Considering the benefits and popularity of cycling, efforts are being made to prevent injury and make the activity more comfortable through proper bike fit.^{59,35,13,12}

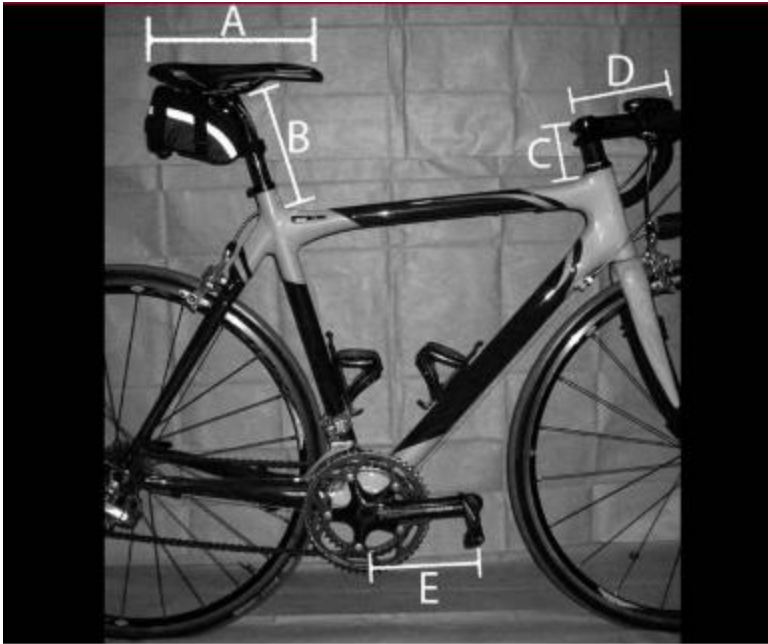
The use of stationary bicycle ergometers as a rehabilitation tool is recommended for patients with knee osteoarthritis, people with Parkinson's disease, and anterior cruciate ligament repair.^{5,3,60,4,61,62,63,64,65} Researchers have suggested that cycling produces favorable knee joint motion (i.e. joint range of motion) during recovery for subjects that have received total knee replacements.⁶⁶ Despite these therapeutic benefits, comfort during cycling greatly varies among individuals due to lack of a proper bike fit. There are many variables that can be manipulated to customize a bicycle fit to an individual. One such variable that has gained popularity amongst clinicians but has been limitedly researched is pedal stance width. Anecdotal evidence suggest that widening pedal stance width can improve comfort and knee joint frontal plane range of motion in individuals with knee pain, however the empirical basis for these observations has not yet been established.

In this literature review, components of the bike fit and how they affect lower extremity range of motion is discussed. Special emphasis is placed on the suggested role of pedaling stance

width and its impact on frontal plane kinematics. In summary, the purpose of this review is to assess the effects of pedal stance width manipulation on lower extremity frontal plane kinematics on a cycle ergometer.

1. Bicycle fit

The geometry and design of a bicycle gives a starting point to cycling fit. Bicycles are also offered in multiple sizes to give cyclists choices to optimize fit. Fit can be manipulated through component exchange and adjustment. The three touchpoints on a bicycle are sometimes called the 3 pivots and include the handlebar, saddle, and pedals.⁶⁷ Many bicycle users purchase components to adjust fit as well as bicycle performance. Components of interest to road cyclists include stem length and height, bar width and angle, seat width and other seat characteristics, crank q-factor (width of crank from pedal insert to pedal insert) and length, and pedal type and axle width.^{40,46} These component adjustments are primarily made to improve performance through optimized biomechanics and physiology.⁶⁸



Photograph of adjustable racing bicycle parts. A = horizontal saddle position, B = vertical saddle position, C = handlebar height, D = handlebar reach, E = crank length

Figure 2. Bicycle fit can be manipulated through component adjustment or replacement.³⁷ In road cycling and cross-country mountain biking specifically, effort is placed on decreasing air resistance, which can be accomplished through aerodynamic bicycle and componentry design as well as rider position.^{11,69} In addition, there are numerous disciplines within road cycling that may affect the goals of fit and available biomechanics. One example is the rear cassette cluster on a geared bicycle. The wider spacing of the rear wheel axle and gears affect how narrow the bottom bracket is and related crank q-factor.⁴⁶ The crank and pedals dictate the total pedal stance width. Bottom bracket width on single-speed road bicycles designed for track racing may have narrower spacing and subsequently a narrower total stance width.

Of more recent interest to both road cycling and mountain biking is pedal stance-width, which is determined by the combination of crank width, pedal axle, and platform width.²⁴ Many variables affect component choices and subsequent bicycle fit. Crank length of normal

componentry does not affect performance metrics such as power output, and should therefore be selected based on fit and injury reduction through changes in hip, ankle, and knee motion.^{42,70} Sagittal plane adjustments are often of primary consideration when fitting a bicycle in order to optimize the position of the trunk and knee, with greater importance placed on the latter.^{7,12,59} Trunk flexion angle is an important component of bike fit related to comfort and should be accounted for when applying changes in seat position.¹² This variable is most easily manipulated through adjustment in handlebar height, but is affected by seat fore-aft, seat height, and seat angle. Some researchers suggest that a bicycle fit should be performed by first making adjustments at the shoulders and trunk prior to inferior manipulations such as knee and ankle position.¹⁵ Bicycle fit is important to increase comfort and it may influence factors such as injury development and physiological performance.^{11,17}

A. Seat height and knee angle

The saddle height and fore-aft position has a great influence on knee flexion angle and is easily manipulated.⁸ The most common fitting techniques to determine seat height utilize a goniometer to measure knee angle at bottom dead center (BDC) of the crank cycle, although traditional static measurements do not always correlate with dynamic techniques.^{7,8} Researchers have investigated inseam length to saddle height ratios and suggest a range of seat positions such as 108.6–110.4% of inseam length, although these calculations do not account for individual anthropometrics and may lead to knee angles outside of the commonly accepted knee angle range of 25-35°.^{8,17} For people with knee pain, increasing saddle height to decrease knee flexion angle may make cycling more comfortable.³⁷ Dynamic techniques such as 3-D recording or 2-D motion capture are more valid than static measurements and should be used when available during bike fitting, however, these are not used as frequently in the literature currently.^{7,44}

Although alternate methods are available for determining sagittal plane fit and movement, motion capture through video is considered the gold standard.⁷¹ Researches interested in integrating kinematic and kinetic data should use pedals with the capability of capturing 3-D forces.⁷²

The saddle of a bicycle may be moved superiorly or inferiorly along the angle of the seat tube and must be considered concomitantly with saddle fore-aft position in order to attain an optimal knee flexion angle of 25-35° at BDC of the crank cycle.^{8,35,73} The variation of seat tube angles across cycling disciplines, manufacturers, and models of bicycles makes this point highly relevant when making vertical adjustments to seat height. Common seat tube angles used in road cycling range from 72-74°, whereas triathlon bikes are steeper at 78-82°.⁷⁴ Modern suspended mountain bikes at the present fall within that total range. There is an important distinction to be made in this regard. Manufacturers typically report effective seat tube angles rather than actual seat tube angles on published geometry documents. The effective seat tube angle can be measured from the bottom bracket center to the point on the seat tube that intersects with a horizontal line drawn from the top of the head to the seat tube.⁶⁶

Effective top tube is measured from top of the head tube posteriorly to the theoretical intersection of the seat tube and varies by size.⁷⁵ This measurement is an indication of how far a rider will sit posterior to the handlebars. On commuting bicycles and many road bicycles this information is fairly helpful as the actual seat tube angle matches the effective angle due to the use of a straight seat tube.⁷⁶ The situation becomes more complicated as frame design caters to suspension design or specialized frame characteristics such as aerodynamics. Mountain bikes often have interrupted seat tubes in order to accommodate suspension designs.⁷⁷ The consequence of this design is that the actual seat tube angle may be very different from the

effective seat tube angle. Because seat height is of primary interest during a bike fit, seat tube angle must be considered when adjusting both seat height and fore-aft position, as both changes may affect sagittal plane ranges of motion such as hip angle.^{8,74,78}

While the knee angle of 25-35° during a bicycle fit is commonly accepted, the methodology of fit is highly variable.^{7,17} It has been suggested that greater knee flexion angles may lead to discomfort and patellofemoral joint pain, which is a common injury due to cycling.^{12,18} Knee angles closer to 25° fall within the suggested range of common bicycle fit and may be more effective in maximizing performance variables such as cycling economy, mean power, and peak power when compared to 35°.¹⁷

It is common to implement a saddle fore-aft position in relation to knee position in the sagittal plane. The pole of the patella in the forward leg should be directly superior to the pedal spindle when crank arms are parallel to the ground.³⁸ This common fit idea prevents many cyclists from experimenting with saddle fore-aft position and does not seem to be based on scientific research, although time trial cyclists often position their knee anterior to the pedal spindle.⁶



Figure 3. An illustration of knee over pedal position.³⁷

Saddle fore-aft manipulates the distance from the seat to the handlebars, which is related to the effective top tube in the sagittal plane. Saddle fore-aft position is actually an extension of seat tube angle, and should be considered based on biomechanical fit, physiological performance, and intended use of the bicycle. Changes in fore-aft may affect economy and lower limb position through creating differences in hip, knee, and ankle angles.⁷⁹ Resultant changes in seat height due to the adjustment of saddle fore-aft must also be considered during bicycle fit.⁶ For the purpose of scientific experimentation, the knee over pedal spindle method should be used during research to remain consistent in bicycle fit unless used as a research variable.⁷

Other manipulations that affect bike-fit in the sagittal plane include saddle tilt, stem length and height, handlebar geometry, and cleat position. Saddle tilt should be close to level on a road bike, and slightly downward on most mountain bikes with full-suspension so that when seated the weight of the rider causes the seat to be approximately level.^{6,18} During seated uphill

cycling, greater downward saddle tilt increases comfort and mimics muscle activation patterns of cycling on level ground with a level seat.¹³

B. Handlebar position and trunk angle

Lower handle bar position is related to increased lumbar flexion and may be related to over-use injury.⁸⁰ Changes in saddle tilt and design may affect weight distribution and trunk angle.⁴⁰ It has been demonstrated that more upright trunk angles are more comfortable than increased trunk flexion.¹² The utilization of greater trunk flexion is commonly adopted for aerodynamic advantages in competitive cyclists.⁶⁹ Increased lumbar flexion concomitant with high volumes of cycling due to a low handlebar position may contribute to spinal adaptations that are unfavorable and may be related to low-back and neck pain.^{11,29}

Researchers have demonstrated that there are no statistically significant differences in kinematics of the leg and foot when comparing upright posture and increased trunk flexion conditions.^{70,81} In regards to their research, controlling for trunk angle may not be required for the purpose of assessing differences in lower leg kinematics. Hip flexion angles may be affected during adjustments to saddle fore-aft position.⁷⁴ One study examining the relationship of seat tube angle, trunk flexion angles, and resulting differences in sagittal plane movement demonstrated that the preferred position of the cyclist is more effective in cycling economy than any of the experimental combinations, which may also be related to comfort.^{12,70}

2. Normal 3-D kinematics

A. Sagittal plane kinematics and relevant bike fit to reduce incidence of injuries

Cycling injuries are commonly due to chronic stresses from over-use, and improper bike-fit has been implicated as a contributing factor.^{12,15,73} The repetitive nature of riding a bicycle

with improper fit or technique may lead to discomfort and pain.³⁷ Sagittal plane fit and kinematics affect comfort and the development of non-traumatic injury through chronic stresses, some of which are developed from non-pedal related work.^{82,83} More upright angles, such as 55° trunk flexion, seem to elicit a more comfortable position than 35° trunk flexion, although experienced cyclists were comfortable in the position with greater flexion.¹² Increased trunk flexion is related to over-use injury and reformation of the lumbar spine.¹¹ To reduce the risk of injury in the present study and for uniformity during data collection, trunk flexion angles of 30° from vertical will be used.^{6,27,73}

The suggested optimal knee angle is widely varied and is likely the most important factor to consider when fitting a bicycle.^{12,15,17,37,73} Greater knee flexion angles such as 40° are associated with acute discomfort and knee pain, while seats fitted too high may lead to hip pain such as trochanteric bursitis and iliotibial band issues.^{12,37} Increases in seat height are positively correlated with increases in knee extension angles and plantar flexion angles during the bottom of the crank cycle, although excessively high saddles may lead to perineal numbness and tingling.^{15,74}



Figure 4. Seat height measured at crank BDC³⁷

Moreover, low saddle positions may lead to Achilles tendonitis, which may worsen with anterior foot fore-aft position on the pedal.¹⁵ More forward saddle positions, which influence seat height and are dependent to a large degree on the geometry of the bicycle, may lead to anterior knee pain as well.³⁷ Whereas posterior knee pain is associated with a saddle position too far back.¹⁵ There are several injuries and discomforts associated with poor bicycle fit in the sagittal plane. Neck pain is associated with a low or forward handlebar position, which may lead to lower back pain from increased trunk flexion.¹⁵ The present study will utilize knee flexion angles of 30° to reduce the risk of injury and remain consistent with the literature.³⁷

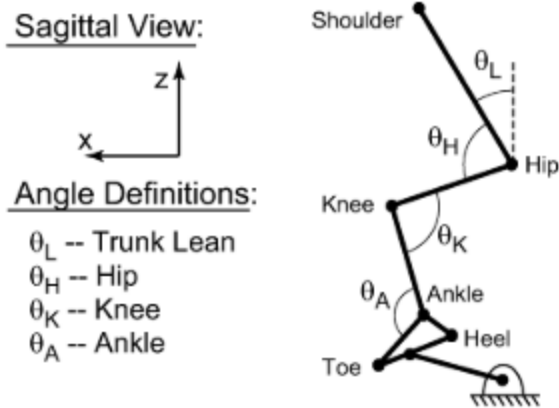


Figure 5. Definition of the sagittal plane angles during cycling.⁶⁸

Sagittal plane range of motion of the hip, knee, and ankle in healthy non-injured young adults while cycling have been reported as follows: Maximal hip flexion angles recorded were $29^\circ \pm 2^\circ$, with maximal hip extension angles of $60^\circ \pm 9^\circ$; maximal knee flexion angles of $77^\circ \pm 11^\circ$, maximal knee extension angles of $133^\circ \pm 13^\circ$; peak dorsiflexion angles of $19^\circ \pm 11^\circ$ and peak plantarflexion angles of $3^\circ \pm 7^\circ$.⁸⁴ Normal ranges of motion (ROM) of the knee and ankle have been reported at 66° and 27° , respectively.³⁶ Others have reported knee and ankle angle ranges of motion to be $57 \pm 10^\circ$ and $21 \pm 2^\circ$, respectively.⁸⁴ Increased ROM such as 75° in

the knee joint and 20° in the ankle joint are considered normal.⁹

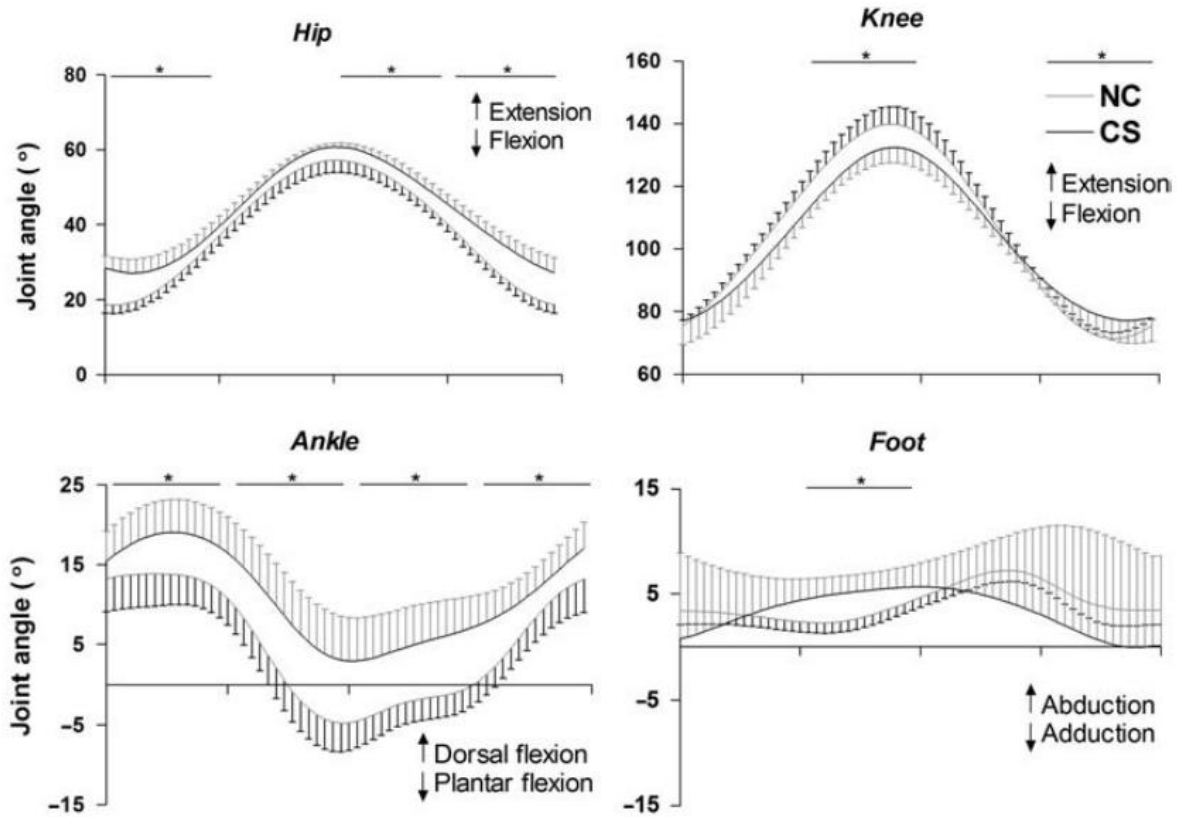


Figure 6. Sagittal plane position traces of the hip, knee, ankle. Frontal plane motion of the foot.⁸⁴

Sagittal plane bicycle fit is critical to achieve comfort, maximize economy, and decrease incidence of injury.¹⁰ Due to the importance of proper bicycle fit in the sagittal plane, frontal plane bike-fit is sometimes overlooked, and further research is warranted to quantify frontal plane kinematics and fit.^{7,12}

B. Frontal plane kinematics and relevant bike fit to reduce incidence of injuries

Little research has been performed to examine frontal plane kinematics of cycling.^{21,46} Overuse injuries may be related to poor biomechanics that primarily affect the knee joint.^{21,24,85} Incorrect fit may negatively affect knee alignment through excessive knee abduction or adduction, especially during the recovery phase of the crank cycle.^{21,85}

Quadriceps angle (Q-angle) in relation to human anatomy is a description of the mechanical action of the patello-femoral joint.⁸⁶ It is defined by the intersection of the line drawn from the anterior superior iliac spine to the patella and the line drawn from the patella to the tibial tubercle.²⁴ Subjects with Q-angles over 10° may be at increased risk of knee pain or injury such as patellofemoral syndrome.^{37,86} Q-angles that cause excessive valgus or varus misalignments of the leg have been identified as contributors to knee pain and reductions of knee valgus may be beneficial in the reduction of injury incidence.^{85,87}

Frontal plane joint motion such as knee adduction in healthy subjects show a large standard deviation of movement in healthy subjects. Researchers found no statistically significant differences as workload increases at the same cadence or during a constant workload with increases in cadence.¹ While pedaling at 60 RPM, healthy cyclists demonstrated knee adduction angles with a range of 5.89 - 7.16° ± 6.44 - 5.96°, suggesting a large variability within frontal plane kinematics at the knee.¹ Knee abduction and adduction ROM of approximately 12° during a study comparing 2-D and 3-D kinematic analysis.⁴⁴ Knee adduction angles such as 8.6° ± 6.7° further define normal frontal plane joint motion during the crank cycle (see figure 6 for traces).²⁶ Injured cyclists differ from healthy cyclists in frontal plane at the point of maximal knee adduction angles, and had a more abducted position.¹⁹

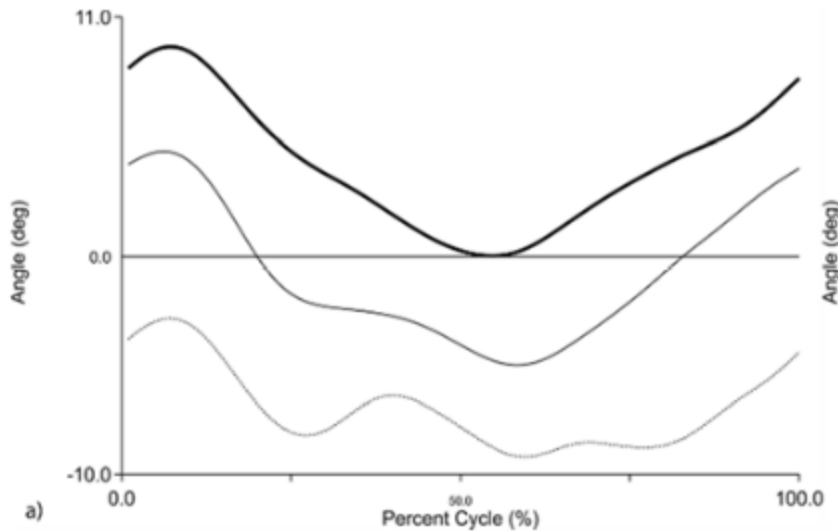


Figure 7. Mean knee adduction angles during cycling. Middle sample is neutral foot placement without a toe clip.²⁶

Q-factor should not be confused with Q-angle, as Q-factor is a measurement of the bicycle crank and is related to pedal stance width. It is defined as the width from pedal insert to pedal insert and ranges from about 150 mm on road bikes to 180 mm on mountain bikes, and 200 mm on fat bikes depending on the bicycle in question.⁴⁶ Q-factor plus the pedal axle length makes up the total stance width. However, pedal stance width may affect Q-angle, making the interaction of the two factors notable.³⁵ Variables such as foot position on the pedals, hip rotation, and pelvic width may affect Q-angle and subsequent frontal plane kinetics.¹

Healthy subjects display different frontal plane kinematics than injured cyclists.³⁵ Changes in pedal stance width through cleat position, crank q-factor, and pedal spindle length may positively affect knee alignment.^{24,35} Incorrect alignment of the patella and the intercondylar groove may contribute to patella-femoral knee pain, which may be related to cleat position.⁸⁸ The foot-shoe-pedal interface manipulations through orthotics is a common practice, yet it has been criticized in its effectiveness and needs further investigation.⁸⁹

Researchers have identified range of motion changes in the frontal plane using novel pedal solutions that allow or guide the cyclist through lateral translation of the ankle on the pedal spindle throughout the crank cycle. Ankle and knee motions were better correlated when cycling with laterally translating pedals, which may improve alignment of the knee and angle and decrease varus and valgus moments.⁹⁰ Although interesting, the practicality of using this type of pedal is poor in most applications. It may be beneficial for use in a bicycle ergometer for rehabilitation purposes. Notably, frontal plane knee motion did not increase to a statistically significant degree with increased ankle translation.⁹⁰ This differs from the present study, in which ankle placement will be placed in differing fixed positions laterally rather than free moving or guided translation during the crank cycle.

3. Strategies to decrease injuries through bike fit

There are a number of bicycle fitting manipulations that are used commonly to reduce injury in cycling.^{6, 73,80,91} These manipulations should begin with making changes to the bicycle fit through manipulations of seat height, seat fore-aft and angle, handlebar height and roll, and cleat position.¹⁵ To be considered concomitantly with these adjustments further include stem length, crank length, shoe inserts or cleat wedges, and pedal stance width.^{6,89} It has been previously discussed that seat height may be the most important factor when fitting a bicycle and that bicycle fit should be performed directionally from superior manipulation to inferior.¹⁵

A. General methods

Saddle height should be high enough to avoid or diminish discomfort at the knee, but not so high as to develop hip pain or perineal discomfort.^{12,74} Seat height adjustments are made to elicit changes in knee flexion and extension angles. Commonly accepted knee flexion angles at

BDC of the crank cycle range from 25°-35°. ^{8,10} Saddle fore-aft adjustments may be used to affect knee angle and trunk angle. Less extreme trunk flexion angles are more comfortable, and should be used unless otherwise necessitated by specific needs such as the reduction of air resistance during road cycling. ¹² Trunk angle can easily be adjusted by moving the handlebars superiorly or inferiorly. ¹

The foot-shoe-pedal interface (FSPI) is popular area of adjustment, however the efficacy of manipulations is controversial. Cleat angle rotation may be helpful in counteracting tibial torsion and reducing knee pain (see figure 8 for neutral cleat position). ³⁵ Shoe wedges may affect knee position in the frontal plane and economy, although the limitations in past research prevents definitive conclusions in this regard. ^{87,89,92} Custom orthotics have been used to create individual adaptations in frontal plane knee motion to decrease knee mediolateral excursion. ⁸⁷

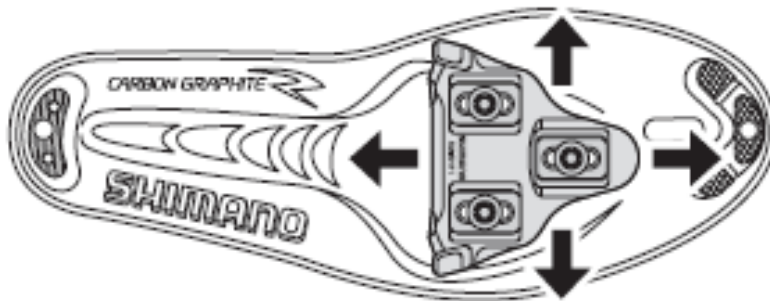


Figure 8. Shimano™ SPD SL cleats can be adjusted 5 mm medio-laterally and 22 mm antero-posteriorly and can also be rotated. ³⁹

Manipulation of stance width

Stance width in cycling is a debated topic in the industry related to fit and performance. It is sometimes considered a fixed variable pre-determined by bicycle design.²⁶ Many cyclists and professional fitters do little or nothing to address stance width, which may be in part related to the limited research available to quantify how stance width affects cycling kinetics and kinematics.⁹³ Stance width can be manipulated in a number of ways, although the bike and its intended use does impact the starting point. Different ways to manipulate stance width are discussed below following an introduction describing the factors affecting the starting point of stance width dependent on bicycle design.

The rear gear cluster, commonly called a cassette on a bicycle, affects the rear hub spacing and subsequent chainstay width. Rear wheel tire clearance also has an effect on chainstay width.⁹⁴ Cranksets are fixed close to the bottom bracket and have are flared outward to clear the chainstay.⁹⁵ The amount of flare combined with the spindle length make up what is called q-factor. Single speed bicycles may have reduced q-factor when compared to geared bicycles due to the narrower chainstay design. Road bikes and mountain bikes have developed increasingly large rear gear clusters that often include 11 or 12 sprockets in the cassette. Fat bikes are growing segment of bicycles that use even wider rear axle spacing to allow for large voluminous tires that can be 4” wide in order to float on snow and sand. These bicycles have larger crank spindles in order to increase q-factor to clear the chainstay.

B. Crankset

Once the bicycle has been selected, the appropriate selection of a crank is the next step in determining stance width.¹⁴ Each bicycle type and model will have a minimum available q-factor

crankset that will fit. Wider cranksets are often available and are dependent on brand and model selection. While it is common to purchase a different crankset from the original equipment, it can be expensive and factors other than fit, such as weight and material, are of primary interest to the consumer rather than comfort.

C. Pedals

After the crank has been selected, pedals are the next variable that can be manipulated due to axle length. Shimano™ (Sakai, Osaka, Japan) is a leading bicycle component manufacturer that makes pedals for all kinds of bikes. The brand offers SPD-SL road bicycle clipless pedals that allow cyclists to mechanically affix their shoes to the pedals in two different axle widths, 52 mm and 56 mm (see figure 9).

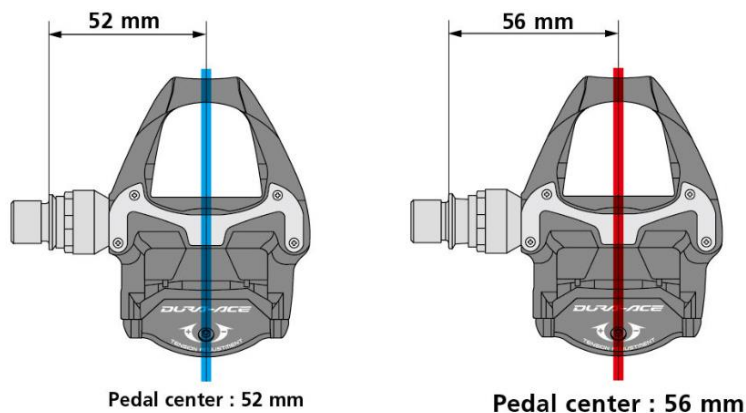


Figure 9. Axle length is measure from crank insertion to pedal centerline.⁴⁸

They advertise that the extended pedal allows cyclists with wider hips to maintain correct leg and foot alignment on the pedals. Another popular brand named Speedplay™ (San Diego, California, USA) offers clipless pedals with three different axle lengths that allow cyclists to change stance width by up to 12.5 mm per pedal, with 53mm being standard. Pedals made by the brand Issi (Bloomington, Minnesota, USA) are 52.5 mm and can be purchased with +6 mm or

+12 mm axles, and axles can be purchased separately and installed. The limited choices for cyclists make it expensive and challenging to experiment with pedal axle length. Therefore, the simplest solution is use of a pedal spacing system.

D. Pedal spacers

After crank selection, pedal and axle selection, pedal spacers provide the largest gains in stance width that can be easily manipulated. One popular brand named Kneesavers™ offer +20 mm and +30 mm options (see figure 10). These large adjustments allow for pedal stance width to cover a broad range of fits when combined with other component choice. Realistically, an axle extender such as the Kneesavers™ (North Hills, California, USA) product is an elegant solution to provide simple manipulations without consideration of crank and pedals based on fit and can be applied to any pedal.



Figure 10. Kneesavers™ Pedal spacers effectively extend pedal width by increasing distance from crank to pedal centerline.⁴⁷

Limited research and anecdotal evidence

There is limited research in the field that quantifies frontal plane mechanics in cycling, especially in relation to pedal stance width. Few studies to date have discussed how pedal stance width affects cycling, and none of them have specifically studied changes in frontal plane kinematics. Researchers found that there was no statistically significant difference in Q-angle or oxygen cost while cycling using +20 mm or + 30 mm pedal spacers from control.²⁴ A follow-up study found that gross mechanical efficiency (GME) improved slightly using a narrower Q-factor, one component of pedal stance width, however they did not publish a kinematic analysis.⁴⁶ Using a hanging test to identify self-selected Q-factor, researchers found that there were no statistically significant differences in GME and knee variability between Q-factors.¹⁴

There are multiple manufacturers and products that suggest the importance of knee alignment, however these claims appear to be based on anecdotal evidence rather than scientific research. Component manufacturers advertise favorable leg and foot alignment and reductions of knee pain, and these should be supported or refuted based on studies using sound methodology.^{48,49} Changes in frontal plane kinematics due to increases in pedal stance width should be quantified so cyclists and fitters can take advantage of this potential adjustment. Cycling kinematics when seated differ from pedaling while standing, and the influence of pedal stance width while out of the saddle warrants further study.⁹¹

Pedal spacers change frontal plane kinematics

Pedal stance width can be manipulated through the use of pedal spacers.^{14,35} Previous research has identified some physiological and biomechanical factors related to increases in pedal stance width, although the impact of these changes on frontal plane joint motion in the

lower extremity is unknown.^{62,89} One study using manipulations of pedal stance width from a starting point of self-selected Q-factor based on a hanging test. There were no statistically significant differences in gross mechanical efficiency or knee variability across different Q-factors.⁶² A study using pedal spacers to increase pedal stance width demonstrated no statistically significant difference in Q-angle or Oxygen consumption using different widths.²⁴ The ease of use and low cost of pedal spacers makes them appealing for study and implementation if found effective.

Summary

In this review of literature, important gaps in the research relevant to understanding how pedal stance width interacts with frontal plane kinematics have been identified. The purpose of this study is to examine the effects of increased pedal stance widths on frontal plane kinematics of the hip, knee, and ankle during stationary cycling while seated. We hypothesize that frontal plane kinematics of the knee will systematically correlate with changes in pedal stance width.

References

1. Fang Y, Fitzhugh EC, Crouter SE, Gardner JK, Zhang S. Effects of workloads and cadences on frontal plane knee biomechanics in cycling. *Med Sci Sports Exerc.* 2016;48(2):260-266. doi:10.1249/MSS.0000000000000759
2. Gardner JK, Zhang S, Liu H, et al. Effects of toe-in angles on knee biomechanics in cycling of patients with medial knee osteoarthritis. *Clin Biomech.* 2015;30(3):276-282. doi:10.1016/j.clinbiomech.2015.01.003
3. van Grinsven S, van Cingel REH, Holla CJM, van Loon CJM. Evidence-based rehabilitation following anterior cruciate ligament reconstruction. *Knee Surgery, Sport Traumatol Arthrosc.* 2010;18(8):1128-1144. doi:10.1007/s00167-009-1027-2
4. Ridgel AL, Peacock CA, Fickes EJ, Kim CH. Active-assisted cycling improves tremor and bradykinesia in Parkinson's disease. *Arch Phys Med Rehabil.* 2012;93(11):2049-2054. doi:10.1016/j.apmr.2012.05.015
5. Halder AM, Graichen F, Heinlein B, et al. Loading of the knee joint during ergometer cycling: telemetric in vivo data. *J Orthop Sport Phys Ther.* 2012;42(12):1032-1038. doi:10.2519/jospt.2012.4001
6. Silberman MR, Webner D, Collina S, Shiple BJ. Road bicycle fit. *Clin J Sport Med.* 2005;15(4):271-276. doi:10.1097/01.jsm.0000171255.70156.da
7. Fonda B, Sarabon N, Li FX. Validity and reliability of different kinematics methods used for bike fitting. *J Sports Sci.* 2014;32(10):940-946. doi:10.1080/02640414.2013.868919
8. Ferrer-Roca V, Roig A, Galilea P, García-Lopez J. Influence of saddle height on lower limb kinematics in well-trained cyclists: static vs. dynamic evaluation in bike fitting. *J Strength Cond Res.* 2012;26(11):3025-3029. doi:10.1519/JSC.0b013e318245c09d
9. Bini RR, Hume PA, Kilding AE. Saddle height effects on pedal forces, joint mechanical work and kinematics of cyclists and triathletes. *Eur J Sport Sci.* 2014;14(1):44-52. doi:10.1080/17461391.2012.725105
10. Bini RR, Bini AF. Potential factors associated with knee pain in cyclists: a systematic review. *Open Access J Sport Med.* 2018;9:99-106. doi:10.2147/OAJSM.S136653
11. Muyor JM, López-Miñarro PA, Alacid F. Spinal posture of thoracic and lumbar spine and pelvic tilt in highly trained cyclists. *J Sport Sci Med.* 2011;10(2):355-361.
12. Priego Quesada JI, Pérez-Soriano P, Lucas-Cuevas AG, Salvador Palmer R, Cibrián Ortiz de Anda RM. Effect of bike-fit in the perception of comfort, fatigue and pain. *J Sports Sci.* 2017. doi:10.1080/02640414.2016.1215496
13. Fonda B, Panjan A, Markovic G, Sarabon N. Adjusted saddle position counteracts the modified muscle activation patterns during uphill cycling. *J Electromyogr Kinesiol.* 2011;21(5):854-860. doi:10.1016/j.jelekin.2011.05.010
14. Disley BX, Li FX. Metabolic and kinematic effects of self-selected Q factor during bike

- fit. *Res Sport Med*. 2014;22(1):12-22. doi:10.1080/15438627.2013.852093
15. M.R. S. Bicycling injuries. *Curr Sports Med Rep*. 2013;12(5):337-345. doi:10.1249/JSR.0b013e3182a4bab7
 16. Chapman AR, Vicenzino B, Blanch P, Hodges PW. Patterns of leg muscle recruitment vary between novice and highly trained cyclists. *J Electromyogr Kinesiol*. 2008;18(3):359-371. doi:10.1016/j.jelekin.2005.12.007
 17. Peveler WW, Green JM. Effects of saddle height on economy and anaerobic power in well-trained cyclists. *J of Strength Cond Res*. 2011;25(3):629-633. doi:10.1519/JSC.0b013e3181d09e60
 18. Callaghan MJ. Lower body problems and injury in cycling. *J Bodyw Mov Ther*. 2005;9(3):226-236. doi:10.1016/j.jbmt.2005.01.007
 19. Bailey MP, Maillardet FJ, Messenger N. Kinematics of cycling in relation to anterior knee pain and patellar tendinitis. *J Sports Sci*. 2003;21(8):649-657. doi:10.1080/0264041031000102015
 20. Sayers MGL, Tweddle AL, Every J, Wiegand A. Changes in drive phase lower limb kinematics during a 60min cycling time trial. *J Sci Med Sport*. 2012;15(2):169-174. doi:10.1016/j.jsams.2011.09.002
 21. Gregersen CS, Hull ML. Non-driving intersegmental knee moments in cycling computed using a model that includes three-dimensional kinematics of the shank/foot and the effect of simplifying assumptions. *J Biomech*. 2003;36(6):803-813. doi:10.1016/S0021-9290(03)00014-9
 22. Hicks-Little CA, Peindl RD, Hubbard TJ, et al. Lower extremity joint kinematics during stair climbing in knee osteoarthritis. *Med Sci Sport Exerc*. 2011;43(3):516-524. doi:10.1249/MSS.0b013e3181f257be
 23. Paquette, MR, Klipple, G, Zhang, S. Greater step widths reduce internal knee abduction moments in medial compartment knee osteoarthritis patients during stair ascent. *J Appl Biomech*. 2015;31(4):229-236. doi:10.1123/jab.2014-0166 LK -
 24. Jensen RL, Watts PB. *The Commons Energy Economy: Effect of Lateral Pedal Width Variations Relative to Q-Angle in Avid Cyclists.*; 2008.
 25. G*Power 3.1 Manual. http://www.gpower.hhu.de/fileadmin/redaktion/Fakultaeten/Mathematisch-Naturwissenschaftliche_Fakultaet/Psychologie/AAP/gpower/GPowerManual.pdf. Published 2017.
 26. Shen G, Zhang S, Bennett HJ, Martin JC, Crouter SE, Fitzhugh EC. Effects of knee alignments and toe clip on frontal plane knee biomechanics in cycling. *J Sport Sci Med*. 2018;17:312-321.
 27. Buddhadev HH, Martin PE. Effects of age, power output, and cadence on energy expenditure and lower limb antagonist muscle coactivation during cycling. *J Aging Phys Act*. 2018;27(1):83-92. doi:10.1123/japa.2017-0400

28. Robinson ME, Plasschaert J, Kisaalita NR. Effects of high intensity training by heart rate or power in recreational cyclists. *J Sport Sci Med.* 2011;10(3):498-501.
29. Schultz SJ, Gordon SJ. Recreational cyclists: The relationship between low back pain and training characteristics. *Int J Exerc Sci.* 3(3):79-85.
30. Buddhadev HH, Crisafulli DL, Suprak DN, San Juan JG. Individuals with knee osteoarthritis demonstrate interlimb asymmetry in pedaling power during stationary cycling. *J Appl Biomech.* 2018;34(4):306-311. doi:10.1123/jab.2017-0363
31. Calibrate a Vicon System. <https://docs.vicon.com/display/Nexus25/Calibrate+a+Vicon+system>. Accessed September 3, 2019.
32. Wiley, G Jr. Does cycling cadence affect interlimb symmetry in pedaling power in individuals with parkinson's disease ? 2018.
33. Lower body modeling with Plugin Gait. <https://docs.vicon.com/display/Nexus25/Lower+body+modeling+with+Plug-in+Gait>. Accessed September 3, 2019.
34. Korff T, Newstead AH, Van Zandwijk R, Jensen JL. Age- and activity-related differences in the mechanisms underlying maximal power production in young and older adults. *J Appl Biomech.* 2014;30(1):12-20. doi:10.1123/jab.2013-0037
35. FitzGibbon S, Vincenzino B, Ann Sisto S. Intervention at the foot-shoe-pedal interface in competitive cyclists. *Int J Sports Phys Ther.* 2016;11(4):637–650.
36. Sanderson DJ, Amoroso AT, Bini RR, et al. The influence of seat height on the mechanical function of the triceps surae muscles during steady-rate cycling. *J Electromyogr Kinesiol.* 2010;21(1):854-860. doi:10.1016/j.jelekin.2008.09.011
37. Wanich T, Hodgkins C, Columbier JA, Muraski E, Kennedy JG. Cycling injuries of the lower extremity. *J Am Acad Orthop Surg.* 2007;15(12):748-756. doi:10.5435/00124635-200712000-00008
38. Burke ER. *High Tech Cycling*. Second. (Burke ER, ed.). Champaign: Human Kinetics; 2003.
39. Shimano Dealer's Manual. <https://si.shimano.com/pdfs/dm/DM-RAPD001-00-ENG.pdf>. Accessed September 3, 2019.
40. Bressel E, Larson BJ. Bicycle seat designs and their effect on pelvic angle, trunk angle, and comfort. *Med Sci Sports Exerc.* 2003;35(2):327-332. doi:10.1249/01.MSS.0000048830.22964.7c
41. Gardner JK, Klipple G, Stewart C, Asif I, Zhang S. Acute effects of lateral shoe wedges on joint biomechanics of patients with medial compartment knee osteoarthritis during stationary cycling. *J Biomech.* 2016;49(13):2817-2823. doi:10.1016/j.jbiomech.2016.06.016
42. Barratt PR, Korff T, Elmer SJ, Martin JC. Effect of crank length on joint-specific power

- during maximal cycling. *Med Sci Sport Exerc.* 2011;43(9):1689-1697. doi:10.1249/mss.0b013e3182125e96
43. Vincent W, Weir J. *Statistics in Kinesiology*. 4th ed. Champaign: Human Kinetics; 2012.
 44. Umberger BR, Martin, PE. Testing the planar assumption during ergometer cycling. *J Appl Biomech.* 2001;17(1):55-62.
 45. Duc S, Bertucci W, Pernin JN, Grappe F. Muscular activity during uphill cycling: Effect of slope, posture, hand grip position and constrained bicycle lateral sways. *J Electromyogr Kinesiol.* 2008;18(1):116-127. doi:10.1016/j.jelekin.2006.09.007
 46. Disley BX, Li FX. The effect of Q Factor on gross mechanical efficiency and muscular activation in cycling. *Scand J Med Sci Sport.* 2014;24(1):117-121. doi:10.1111/j.1600-0838.2012.01479.x
 47. Kneesavers Products. <http://www.kneesaver.net/shop---products.html#!/Kneesavers-Road-Mountain-Hybrid-or-Recumbent-Bikes/p/66655946/category=0>. Accessed September 3, 2019.
 48. 4 mm Longer Axle. <https://bike.shimano.com/en-EU/technologies/component/details/pedal-4mm.html>. Accessed September 3, 2019.
 49. Pedal Stance Width ISSI. <https://rideissi.com/articles/stance-width-and-why-its-important>. Accessed September 3, 2019.
 50. Dill J. Bicycling for transportation and health: The role of infrastructure. *J Public Health Policy.* 2009;30(SUPPL. 1):95-110. doi:10.1057/jphp.2008.56
 51. Castillo-Manzano JI, Sánchez-Braza A. Can anyone hate the bicycle? The hunt for an optimal local transportation policy to encourage bicycle usage. *Env Polit.* 2013;22(6):1010-1028. doi:10.1080/09644016.2012.740936
 52. Godbey G. Outdoor recreation, health, and wellness: understanding and enhancing the relationship. *Ssrn.* 2009;(May). doi:10.2139/ssrn.1408694
 53. Strath SJ, Isaacs RF, Greenwald MJ. Operationalizing environmental indicators for influencing physical activity in the elderly. *J Phys Act Aging.* 2007;15(4):412-424. doi:10.1123/japa.15.4.412
 54. Karavirta L, Häkkinen K, Kauhanen A, et al. Individual responses to combined endurance and strength training in older adults. *Med Sci Sports Exerc.* 2011;43(3):484-490. doi:10.1249/MSS.0b013e3181f1bf0d
 55. Huy C, Klein T, Thiel A, Becker S, Gomolinsky U. Health, medical risk factors, and bicycle use in everyday life in the over-50 population. *J Aging Phys Act.* 2016;16(4):454-464. doi:10.1123/japa.16.4.454
 56. Oja P, Titze S, Bauman A, et al. Health benefits of cycling: a systematic review. *Scand J Med Sci Sport.* 2011;21(4):496-509. doi:10.1111/j.1600-0838.2011.01299.x
 57. Bucksch J. Physical activity of moderate intensity in leisure time and the risk of all cause mortality. *Br J Sports Med.* 2005;39(9):632-638. doi:10.1136/bjism.2004.015768

58. Lusk AC, Mekary RA, Feskanich D, Willett WC. Bicycle riding, walking, and weight gain in premenopausal women. *Arch Intern Med.* 2010;170(12):1050-1056. doi:10.1001/archinternmed.2010.171
59. Clarsen B, Krosshaug T, Bahr R. Overuse injuries in professional road cyclists. *Am J Sports Med.* 2010;38(12):2494-2501. doi:10.1177/0363546510376816
60. Mavroidis C, Gade VK, Ranky RG, Deutsch JE, Lewis JA, Sivak ML. Modular mechatronic system for stationary bicycles interfaced with virtual environment for rehabilitation. *J Neuroeng Rehabil.* 2014;11(1):93. doi:10.1186/1743-0003-11-93
61. Lewis SF, Marchetti G, Salacinski AJ, Holland ML, Ireland K, Krohn K. The effects of group cycling on gait and pain-related disability in individuals with mild-to-moderate knee osteoarthritis: a randomized controlled trial. *J Orthop Sport Phys Ther.* 2012;42(12):985-995. doi:10.2519/jospt.2012.3813
62. Aerts M, Abdo W, Bloem B. The “bicycle sign” for atypical parkinsonism. *Lancet.* 2011;377(9760):125-126. doi:10.1016/s0140-6736(11)60018-4
63. Li C-WC, Taylor D, Bierma-Zeinstra SMA, Maher CG. Exercise for osteoarthritis of the knee. *Br J Sports Med.* 2016;50(16):1013-1014. doi:10.1136/bjsports-2016-096104
64. Wainwright TW, Immins T, Middleton RG. A cycling and education programme for the treatment of hip osteoarthritis: a quality improvement study. *Int J Orthop Trauma Nurs.* 2016;23:14-24. doi:10.1016/j.ijotn.2016.02.004
65. Roberts D, Ageberg E, Andersson G, Fridén T. Effects of short-term cycling on knee joint proprioception in ACL-deficient patients. *Knee Surgery, Sport Traumatol Arthrosc.* 2004;12(5):357-363. doi:10.1007/s00167-003-0468-2
66. Hamai S, Miura H, Higaki H, et al. Three-dimensional knee joint kinematics during golf swing and stationary cycling after total knee arthroplasty. *J Orthop Res.* 2008;26(12):1556-1561. doi:10.1002/jor.20671
67. Xiuhua Z, Zhongdong D, Chunwei Z. Numerical simulation of dynamic response and collapse for steel frame structures subjected to blast load. *Trans Tianjin Univ.* 2008;14(043186211):523-529. doi:10.1007/s12209
68. Dingwell JB, Joubert JE, Diefenthaler F, Trinity JD. Changes in muscle activity and kinematics of highly trained cyclists during fatigue. *IEEE Trans Biomed Eng.* 2008;55(11):2666-2674. doi:10.1109/TBME.2008.2001130
69. Bertucci WM, Rogier S, Reiser RF. Evaluation of aerodynamic and rolling resistances in mountain-bike field conditions. *J Sports Sci.* 2013;31(14):1606-1613. doi:10.1080/02640414.2013.792945
70. Heil DP, Derrick TR, Whittlesey S. The relationship between preferred and optimal positioning during submaximal cycle ergometry. *Eur J Appl Physiol Occup Physiol.* 1997;75(2):160-165. doi:10.1007/s004210050141
71. Horscroft RD, Elmer SJ, Martin JC, Shultz BB, Brown NAT. A low-cost instrumented spatial linkage accurately determines ASIS position during cycle ergometry. *J Appl*

- Biomech.* 2016;23(3):224-229. doi:10.1123/jab.23.3.224
72. Ruby P, Hull ML, Hawkins D. Three-Dimensional knee joint loading during seated cycling. *J Biomech.* 1992;25(1):41-53.
 73. Bini R, Hume PA, Croft JL. Effects of bicycle saddle height on knee injury risk and cycling performance. *Sport Med.* 2011;41(6):463-476. doi:10.2165/11588740-000000000-00000
 74. Price D, Donne B. Effect of variation in seat tube angle at different seat heights on submaximal cycling performance in man. *J Sports Sci.* 1997;15(4):395-402. doi:10.1080/026404197367182
 75. Gologlu C, Mizrak C. An integrated fuzzy logic approach to customer-oriented product design. *J Eng Des.* 2011;22(2):113-127. doi:10.1080/09544820903032519
 76. Morris R, Begg S, Covill D, Katz T, Elton E, Milne M. Parametric Finite Element Analysis of Bicycle Frame Geometries. *Procedia Eng.* 2014;72:441-446. doi:10.1016/j.proeng.2014.06.077
 77. Ishii T, Umemura Y, Kitagawa K. Influences of mountain bike suspension systems on energy supply and performance. *Japanese J Biomech Sport Exerc.* 2003;7:2-9.
 78. Cruz-Ferreira A, Fernandes J, Laranjo L, Bernardo LM, Silva A. A systematic review of the effects of pilates method of exercise in healthy people. *Arch Phys Med Rehabil.* 2011;92(12):2071-2081. doi:10.1016/j.apmr.2011.06.018
 79. Diefenthaler F, Bini RR, Laitano O. Assessment of the effects of saddle position on cyclists' pedaling technique. *Med Sci Sport Exerc.* 2006;38(Supplement):77. doi:10.1249/00005768-200605001-00821
 80. Streisfeld GM, Bartoszek C, Creran E, Inge B, McShane MD, Johnston T. Relationship between body positioning, muscle activity, and spinal kinematics in cyclists with and without low back pain: A systematic review. *Sports Health.* 2017;9(1):75-79. doi:10.1177/1941738116676260
 81. Chapman AR, Vicenzino B, Blanch P, Knox JJ, Dowlan S, Hodges PW. The influence of body position on leg kinematics and muscle recruitment during cycling. *J Sci Med Sport.* 2008;11(6):519-526. doi:10.1016/j.jsams.2007.04.010
 82. Macdermid PW, Fink PW, Stannard SR. Transference of 3D accelerations during cross country mountain biking. *J Biomech.* 2014;47(8):1829-1837. doi:10.1016/j.jbiomech.2014.03.024
 83. Kennedy J. Neurologic injuries in cycling and bike riding. *Phys Med Rehabil Clin N Am.* 2009;20(1):241-248. doi:10.1016/j.pmr.2008.10.015
 84. Carpes FP, Dagnese F, Mota CB, Stefanyshyn DJ. Cycling with noncircular chainring system changes the three-dimensional kinematics of the lower limbs. *Sport Biomech.* 2009;8(4):275-283. doi:10.1080/14763140903414409
 85. Faria EW, Parker DL, Faria IE. The Science of Cycling part 1. *Sport Med.*

- 2005;35(4):313-337. doi:10.2165/00007256-200535040-00003
86. Herrington L, Nester C. Q-angle undervalued? The relationship between Q-angle and medio-lateral position of the patella. *Clin Biomech.* 2004;19(10):1070-1073. doi:10.1016/j.clinbiomech.2004.07.010
 87. Graham K, Perry P, O'Neill BC, Kuah D, Moresi M. Custom formed orthoses in cycling. *J Sci Med Sport.* 2011;14(6):529-534. doi:10.1016/j.jsams.2011.04.002
 88. Dettori NJ, Norvell DC. Non-traumatic bicycle injuries: A review of the literature. *Sport Med.* 2006;36(1):7-18. doi:10.2165/00007256-200636010-00002
 89. Yeo BK, Bonanno DR. The effect of foot orthoses and in-shoe wedges during cycling: A systematic review. *J Foot Ankle Res.* 2014;7(1). doi:10.1186/1757-1146-7-31
 90. McCulloch RS. Influence of lateral pedal translation on muscle recruitment and kinematics in cyclists. *J Exerc Sci Fit.* 2018;16(2):62-67. doi:10.1016/j.jesf.2018.06.002
 91. Fonda B, Šarabon N. Biomechanics and energetics of uphill cycling: a review. *Kinesiology.* 2012;44(1):5-17.
 92. Sanderson DJ, Black AH, Montgomery J. The effect of varus and valgus wedges on coronal plane knee motion during steady-rate cycling. *Clin J Sport Med.* 1994;4(2):120-124. doi:10.1097/00042752-199404000-00009
 93. Barrett E. Q factor in cycling: kinematic and physiological effects. *Thesis.* 2013. doi:10.1016/0197-3975(91)90016-E

94. Francois M. "Design and manufacturing of a welding-jig for tailor-made bicycle frames".
95. Collins PK, Leen R, Gibson I. Industry case study: rapid prototype of mountain bike frame section. *Virtual Phys Prototyp*. 2016;11(4):295-303.
doi:10.1080/17452759.2016.1222563

APPENDIX A

Western Washington University Informed Consent

The effects cycling with wider pedal stances on joint motion and comfort in young recreational cyclists

We are asking you to be in a research study. Participation is voluntary. The purpose of this form is to give you the information you will need to help you decide whether to participate. Please read the form carefully. You may ask questions about anything that is not clear. When we have answered all of your questions, you can decide if you want to be in the study or not. This process is called “informed consent.”

Purpose and Benefit:

This research aims to examine the effects of different widths on cycling stance (i.e. cycling with feet more apart) on joint motion and comfort in young recreational cyclists. There is anecdotal evidence to suggest that cycling with wider stance increases knee joint comfort in people with knee pain, however, there is no research data to support this claim. The study will increase our current understanding of the effects pedal stance widths on joint motion and comfort in young recreational cyclists.

The participant understands that:

- Participation will require approximately a 1-hour time commitment.
- To be eligible for this research, participants should:
 - be between the ages of 18 and 35 years
 - be a recreational cyclist: during the majority of the past year, have cycled, (indoors or outdoors) for transportation, recreation, and/or exercise
 - not have any recent injuries or pain in the legs that would make cycling uncomfortable
- Participant is aware that the testing session at Western Washington University will begin with completing the informed consent document. Participant will also complete a health history questionnaire. The healthy history survey will help researchers confirm that he or she qualifies for the project.
- Participant’s height and weight, leg length and girth will be measured.
- Testing session will be conducted while the participant is wearing spandex clothing and cycling shoes and reflective markers placed on the shoes, clothes and the skin.
- Next the stationary cycle will be adjusted according to the participant’s body size.
- The participant will then perform a 5-minute warm-up at a comfortable resistance and speed.

- Next the participant will complete 3 cycling trials each lasting 5-minutes. The participant will have the freedom to select the pedaling resistance and the speed. This resistance and speed will be kept the same for the three cycling trials.
- The three pedaling trials are:
 - a. Cycling with feet in normal cycling position
 - b. Cycling with feet apart. Pedal spacers (2 cm spacers and 3 cm spacers) will be placed on the pedal such that they make the pedals go slightly more apart from the center of the bicycle.
- During the cycling trials, the researcher will collect data from the cameras (regarding the movement of the markers), and also ask the participant to gauge their comfort from 0-10 during the cycling trials.
- A 3-5 minute rest period will separate the cycling trials. If needed the participants can rest longer than 5 minutes between trials.
- There are minimal risks from participation in this research. Participant may experience some mild fatigue from the cycling trials.
- The participant understands that there are no potential direct benefits from participation in this study.
- Participation is completely voluntary. Participants are able to withdraw from this research at any time without penalty or loss of benefits to which they are otherwise entitled.
- All information is confidential. Participants will be given an ID number for this study, which will be used to label their data. The link between this ID number and the participant's name and other identifying information will be stored separately. Only the primary investigators will have access to the data collected from this study. After the study ends, the link between the participant's name and their study ID will be deleted.
- Participant signature on this form does not waive any legal rights of protection.
- A physical copy of this informed consent form will be provided to the participant upon arrival at the laboratory.

This research is conducted by Andrew Fife under the supervision of Dr. Harsh Buddhadev. Any questions that you have regarding the study or your participation may be directed to Andrew Fife at fifea@wwu.edu or Dr. Harsh Buddhadev at harsh.buddhadev@wwu.edu.

If you have any questions about your participation or your rights as a research participant, you can contact the WWU Office of Research and Sponsored Programs (RSP) at compliance@wwu.edu or (360) 650-2146. If during or after participation in this study you suffer from any adverse effects as a result of participation, please notify the researcher directing the study or the RSP.

By signing below you are saying that you have read this form, that you have had your questions answered, that you understand the tasks involved, and volunteer to take part in this research.

I have read the above description and agree to participation in this study.

Participant's Signature: _____ Date: _____

Participant's Printed Name: _____

APPENDIX B

Table 2. Effect of stance width condition on lower extremity sagittal plane joint kinematics

	Female			Male			Sex main effect	Condition main effect	Sex-condition interaction
	No spacer	2 cm spacer	3 cm spacer	No spacer	2 cm spacer	3 cm spacer			
Hip flexion maximum (°)	87.6 (5.1)	87.5 (5.5)	88.1 (5.2)	86.3 (6.2)	85.9 (5.9)	86.1 (5.7)	$F_{1,22}=0.56; p=0.464; \eta_p^2=0.025$	$F_{2,44}=0.81; p=0.453; \eta_p^2=0.035$	$F_{2,44}=0.77; p=0.471; \eta_p^2=0.034$
Hip flexion minimum (°)	40.2 (6.3)	39.6 (6.5)	39.8 (6.4)	43.8 (6.6)	42.8 (6.8)	43.1 (6.3)	$F_{1,22}=1.64; p=0.213; \eta_p^2=0.069$	$F_{2,44}=3.78; p=0.043; \eta_p^2=0.147^*$	$F_{2,44}=0.22; p=0.804; \eta_p^2=0.010$
Hip Sagittal plane ROM (°)	47.4 (2.4)	48.0 (2.9)	48.4 (3.1)	42.5 (2.3)	43.1 (2.6)	43.0 (2.6)	$F_{1,22}=21.92; p<0.001; \eta_p^2=0.499^*$	$F_{2,44}=10.85; p=0.001; \eta_p^2=0.330^*$	$F_{2,44}=1.65; p=0.210; \eta_p^2=0.070$
Knee flexion maximum (°)	112.8 (4.1)	112.6 (4.2)	112.1 (4.0)	108.9 (4.3)	108.6 (4.3)	108.4 (4.1)	$F_{1,22}=5.24; p=0.032; \eta_p^2=0.192^*$	$F_{2,44}=7.59; p=0.002; \eta_p^2=0.257^*$	$F_{2,44}=0.65; p=0.528; \eta_p^2=0.029$
Knee flexion minimum (°)	33.6 (7.4)	33.3 (8.0)	32.4 (7.5)	35.6 (6.5)	34.5 (6.0)	35.4 (5.7)	$F_{1,22}=0.55; p=0.468; \eta_p^2=0.024$	$F_{2,44}=3.75; p=0.029; \eta_p^2=0.151^*$	$F_{2,44}=4.76; p=0.013; \eta_p^2=0.178^*$
Knee Sagittal plane ROM (°)	79.3 (5.2)	79.3 (5.4)	79.7 (5.1)	73.4 (3.7)	74.1 (3.5)	73.1 (3.3)	$F_{1,22}=10.60; p=0.004; \eta_p^2=0.325^*$	$F_{2,44}=2.42; p=0.100; \eta_p^2=0.099$	$F_{2,44}=7.08; p=0.002; \eta_p^2=0.243^*$
Ankle dorsiflexion maximum (°)	7.9 (8.5)	7.0 (7.8)	7.3 (8.3)	9.7 (7.5)	9.3 (8.5)	8.7 (8.4)	$F_{1,22}=0.32; p=0.580; \eta_p^2=0.014$	$F_{2,44}=1.54; p=0.225; \eta_p^2=0.065$	$F_{2,44}=0.43; p=0.633; \eta_p^2=0.019$
Ankle plantarflexion minimum (°)	13.2 (6.3)	12.8 (5.8)	12.8 (5.8)	11.5 (6.5)	11.2 (6.7)	11.7 (6.2)	$F_{1,22}=0.34; p=0.568; \eta_p^2=0.015$	$F_{2,44}=0.49; p=0.618; \eta_p^2=0.022$	$F_{2,44}=0.32; p=0.729; \eta_p^2=0.014$
Ankle Sagittal plane ROM (°)	21.1 (4.1)	19.7 (4.2)	20.1 (4.1)	21.2 (5.8)	20.5 (6.4)	20.4 (7.3)	$F_{1,22}=0.03; p=0.857; \eta_p^2=0.002$	$F_{2,44}=3.02; p=0.059; \eta_p^2=0.121$	$F_{2,44}=0.23; p=0.795; \eta_p^2=0.010$

* Values are Mean (SD); * statistically different

Instructions for Authors

Journal of Applied Biomechanics

The *Journal of Applied Biomechanics (JAB)* disseminates the highest quality peer-reviewed studies that utilize biomechanical strategies to advance the study of human movement. Areas of interest include clinical biomechanics, gait and posture mechanics, musculoskeletal and neuromuscular biomechanics, sport mechanics, and biomechanical modeling. Studies of sport performance that explicitly generalize to broader activities, contribute substantially to fundamental understanding of human motion, or are in a sport that enjoys wide participation, are welcome. Also within the scope of *JAB* are studies using biomechanical strategies to investigate the structure, control, function, and state (health and disease) of animals.

I. Types of Manuscripts

JAB accepts six types of manuscripts, which are described below. The word count limitations pertain to the Introduction section through the Discussion section.

Original Research Article: Presents the results of a hypothesis-driven study or, in some cases, a descriptive study, the results of which are considered novel and important. Original Research Articles should not exceed 4,000 words or include more than 8 figures/tables.

Technical Note: Presents a new or modified method or instrument, or an important experimental observation. Technical Notes should not exceed 2,000 words or include more than 4 figures/tables.

Computational Model Article: Presents novel and important model development and/or application. Authors are required to address issues of model validation, sensitivity, and limitations as appropriate. Supplemental information (e.g. equations, visualizations, and data) can be made available online. Computational Model Articles should not exceed 4,000 words or include more than 8 figures/tables.

Review Article: Presents a critical and inclusive overview of a topic of scientific and/or clinical importance in biomechanics. The role of Review Articles in *JAB* is to provide a stimulus for further systematic biomechanical inquiry. This requires that a presumably large body of accumulated literature is summarized so as to illuminate gaps in the state of knowledge. These gaps can be revealed by identifying conflicting evidence, problems borne of methodological disparities and/or inadequacies, the influence of invalid or unproven assumptions, and the potential for alternative interpretations. Collectively, these gaps should lead to establishing explicit and testable hypotheses. Such reviews should be forward looking and should not merely report the current state of the art. Please e-mail the Editor-in-Chief Michael Madigan (mlm@vt.edu) if you are interested in submitting a Review Article for consideration. This email should include an abstract and a brief statement of expertise of the author(s) on the topic of the review, which can simply be a list of publications on the topic. Review Articles should not exceed 6,000 words or include more than 8 figures/tables.

Updated Mar 2019

Target Article: Presents a summary of current scientific thought from the unique perspective of an experienced scientist on a matter of significance to the field of biomechanics. Invited responses to the Target Article and the author's rebuttal can be published along with the Target Article. Target Articles are designed to stimulate thinking and research ideas relating to the topic. Please e-mail Editor-in-Chief Michael Madigan (mlm@vt.edu) if you are interested in developing a Target Article.

Book Review: Please e-mail Editor-in-Chief Michael Madigan (mlm@vt.edu) if you are interested in submitting a book review for consideration. Book Reviews should not exceed 1,000 words.

Please note that JAB has a general policy of not accepting papers that have a primary focus on the reliability, validity, or accuracy of commercially-available products. We have found that such papers tend to be poorly cited and, hence, have at most a modest impact in the field.

II. Cover Letter

A cover letter must accompany all submissions. The cover letter should include the following items:

A. Manuscript title

B. Type of manuscript

C. A statement that all authors satisfy the criteria for authorship as outlined by the International Committee of Medical Journal Editors (available at www.icmje.org). Each author must meet all 4 criteria: 1. Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work

2. Drafting the work or revising it critically for important intellectual content

3. Final approval of the version to be published

4. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

*Individuals who do not meet the above criteria may be listed in the acknowledgments section of the manuscript.

D. A statement that the manuscript has not been published elsewhere, and is not under consideration for publication elsewhere.

E. List of all authors. The corresponding author may sign on behalf of all authors.

F. If the author(s) are submitting a Review Article, the cover letter should also include a brief statement of expertise within the topic of the review, which can simply be a list of publications on the topic.

III. Manuscript Preparation

All manuscripts must be written in English, with attention to concise language, a logical structure and flow of information, and correct grammar. We appreciate that some of our authors do not speak English as their first language and may need assistance to reach the standards required by the journal. In addition, some younger authors may not be experienced in scientific writing styles. Since manuscripts that fail to meet the journal's writing standards will not be sent out for

Updated Mar 2019

. This information does not constitute endorsement of this service. Use of an editorial service is at the discretion and cost of the authors, and will not guarantee acceptance for publication in *JAB*.

instrument applied a 2.5 MPa stress to the tissue” (no hyphen, or dash, between 2.5 and MPa).

5. Use the exponent style for multiple units, rather than the solidus (slash) style without parentheses: Use $-21.25 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ instead of -21.25 J/kg/m .

- E. Additional Formatting Preferences**
1. Always use commas and semi-colons in a series to separate the items. The comma is the mandatory first-order separator, and the semi-colon is reserved to function only as the second-order separator, as in, “sports, exercise, and physical activity; randomized, double-blind, controlled trials; and enthusiasm, organization, and commitment. . . .” Always include the comma or semi-colon, as appropriate, before the conjunction word (and, or, but).
 2. The semi-colon is used only to separate, and never to introduce.
 3. The colon is used to introduce.
 4. Capitalize only the very few kinds of words specified in the AMA style manual, such as persons’ names. If in doubt, use lowercase.
 5. Use acronyms and abbreviations sparingly. Spell out a term at each instance if you use it only 2–3 times. Differentiate between abbreviations (usually lowercase letters) and acronyms (all capital letters). Always use the spelled-out form to begin a sentence. Once you introduce an acronym, keep using it and do not revert to use of the spelled-out term.
 6. In the text, parentheses should always surround the brackets: ([. . .]).
 7. In math, always use the multiplication sign (\times) or centered dot (\cdot), but never the asterisk. In text, type a space on both sides of all operators, or allow the math software to apply standard spacings. Separate the operations using brackets and parentheses: { . . . [. . . (. . .) . . .] . . . }
 8. Leave no spaces before, between, and after any subscript or superscript.
 9. Never use the Tab key except to indent the first line of a paragraph.

IV. Review Criteria

Manuscripts will initially be screened by the Editorial staff to determine whether it fits within the scope of *JAB*, has the potential for a positive review, and complies with the requested format and organization. Following this initial screening, *JAB* uses a single-blinded review process where the identity of the authors is revealed to the reviewers, but not vice versa. Manuscripts are peer-reviewed by the Editorial Board and reviewers according to the following general criteria:

- A. Significance or importance of the topic or problem to the field
- B. Originality of the research question(s) or goal(s) of the study
- C. Scientific quality of the methodology, results, and interpretation of the results
- D. Clarity and conciseness of the writing
- E. Potential impact on the field
- F. Interest to the readership

V. Revised Manuscripts

Following peer review, it is common for revisions to be requested. As part of the revision process, please create a document that provides a point-by-point response to the reviewer

Updated Mar 2019

comments. This document should alternate between each reviewer comment (pasted verbatim from the review), and your response to that comment. State specifically where in the manuscript you revised the text, table, and/or figure in response to the reviewer's concern, and underline added or changed text in the revised manuscript (do not use the track changes feature in Microsoft Word). If you choose not to revise the manuscript on a particular point, clearly state so and justify your decision.

During submission of your revised manuscript, upload your point-by-point response as a "Supplementary File", and update the order so that this file appears prior to the revised manuscript. This will ensure your response appears first in the PDF compiled by ScholarOne.

On the Title Page, write the *JAB* manuscript ID number followed by ".R1" for a first revision, ".R2" for a second revision, and so on.