Journal of Science & Cycling
Breakthroughs in Cycling & Triathlon Sciences

OPEN ACCESS

Original Article

Effect of Seat Shear Forces and Pressure on Perceived Sitting Comfort in Cycling

Victor Scholler [1,2,*], Alain Groslambert [1,2] and Frederic Grappe [1,2,3]

[1] EA4660, C3S Culture Sport Health Society, University of Bourgogne Franche-Comté, Besançon, France
[2] Laboratory of Athlete-Material-Environment (LAME), 56 chemin des Montarmots, 25000, Besançon, France
[3] Equipe Cycliste Groupama-FDJ, Besançon, France

* Correspondence: Victor Scholler, victor.scholler@orange.fr

Received: 20 December 2022; Accepted: 3 April 2023; Published: 30 June 2023

Abstract: Feeling comfortable on the bicycle is essential for professional cyclists to decrease pain and prevent pathologies. The pressure analysis appears to be a relevant tool to monitor how the changes in position and saddle characteristics affect the stress on genital tissues to prevent pathologies. Moreover, in everyday life sitting situations, other biomechanical sitting parameters such as shear forces influence the sitting comfort. Therefore, this study aimed to identify how the seat pressure and shear forces affect the perceived sitting comfort of twelve competitive road cyclists during a 20 min treadmill cycling exercise. Treadmill exercises were performed before and after a fitting optimization session that aimed to improve the perceived sitting comfort. The major result is that the fitting optimization session significantly improved the perceived sitting comfort by 77%. Such improvement was associated with the decrease in shear forces (-21 ± 42%) applied by the cyclist on the saddle in the lateral-medial direction and the increase in peak pressure at sit bone left (+19 ± 25%) and right (+28 ± 63%) following the fitting optimization session. It would be induced by better stability of the cyclist's pelvic on the saddle, therefore reducing the proportion of the shear forces applied on the saddle.

Keywords: saddle; comfort; shear forces; pressure; biomechanics

1. Introduction

It is crucial for cyclists who spent approximately 800 hours per year on their bikes to feel comfortable to prevent pathologies. The sitting comfort during cycling (Hynd, Cooley, & Graham, 2017; Larsen et al., 2018) strongly influences the global comfort of the bicycle (Ayachi, Dorey, & Guastavino, 2015). Many factors such as the bicycle setting, the saddle tilt, and the saddle characteristics (Hynd et al., 2017; Larsen et al., 2018) contributed to the sitting comfort on the bicycle. Hence, determining the relevant settings and saddle characteristics is important to optimise the comfort and prevent saddle-related pathologies (Sommer, 2003; Spears et al., 2003). Therefore, bike-fitting practitioners need to have objectives criteria of measures to recommend an adapted saddle.

A few studies explained how the saddle characteristics and bicycle settings affected the sitting comfort of cyclists. (Chen & Liu, 2014) reported that during a 20 min cycling exercise at 120 W and 60 rotation per min (rpm), a saddle nose of 6 cm improved the perceived sitting comfort at the perineal and ischiatic regions compared to a saddle with a nose of 0, 3, 9 and 12 cm length. The authors explained that this would be due to a pressure homogeneously reparteed between the pubic bone and sit bones. Moreover, (Hynd et al., 2017) reported that the saddle tilt influenced the perceived sitting comfort of 13 men and 4 women. Hence, changes in sitting comfort would depend on the pelvic pose on the saddle, which is influenced by saddle characteristics, saddle tilt, and the position (Carpes, Dagnese, Kleinpaul, de Assis Martins, & Bolli Mota, 2009; Sommer, 2003). Since the comfort seemed to be affected by the position of the pelvic on the saddle, it could be relevant to characterize the pelvic-saddle interface using objective measurements.

The pressure mapping system used was a relevant system since it allowed discriminating the pressure induced by 4 different saddles during a cycling exercise at 250 W and 90 rpm (Lowe, Schrader, & Breitenstein, 2004). Rodano et al., (2002) explained that some saddle characteristics such as the nose length, the saddle width, and the presence of a perineal area hole had an impact on the measured pressure and involved stress on sensitive tissues saddles during a cycling exercise at 150 W and 70 rpm. During a 20 min cycling exercise at 150 W, the presence of a cutout on the nose of the saddle increased the pressure in the anterior part of the saddle that increased the perceived discomfort at the ischial tuberosities (Larsen et al., 2018). Finally, in a forward trunk position (60°), a holed saddle significantly decreased the mean pressure of 11 recreational cyclists in static position (55.75 kPa compared to 63.38 kPa for a plane saddle).

Moreover, in everyday life sitting situations, other biomechanical sitting parameters seemed to influence the sitting comfort. Indeed, shear forces on sensitive buttock tissues would imply frictions and distortions on the skin surface leading to pathologies like occlusions and necrosis (Zhang, Turner-Smith, & Roberts, 1994). An adjustable vehicle seat was designed to measure these shear forces and improve the ergonomics of seats in modes of transport (Beurier, Cardoso, & Wang, 2017). This seat was adjustable to allow people to select their preferred configuration of seat height, leg rest, lumbar support, and head support. Results of this study reported that the shear forces were lower when the seat was adjusted according to the participant's preferences, suggesting that shear forces should be reduced to improve the seating comfort. Even if the bicycle seat is different to seats in modes of transport, the cyclists also applied shear forces on their saddle during pedaling, which could also impair the perceived sitting comfort during cycling. Indeed, (Wilson & Bush, 2007) reported that during a pedaling exercise at 125 W and 75 rpm, the shear forces in the anterior-posterior and lateral-medial direction were 11-12% and 4-5% of the cyclist’s body weight, respectively. To the best of our knowledge, no studies investigated the effect of shear forces on the sitting comfort during cycling.

Hence, we think that the pose of sit bones and pubic bone on a saddle would improve the perceived sitting comfort since this would limit the contact with soft sensible tissues. It would also increase the stability of the pelvic on the saddle, therefore reducing the shear forces on sensible tissues.

Therefore, this study aimed to identify how the seat pressure and the seat shear forces affected the subjective perceived sitting comfort of cyclists (Chen & Liu, 2014) during a treadmill pedaling exercise at a moderate intensity performed at different slopes to reproduce different ecological conditions. The position on the bicycle and the saddle characteristics were modified during a fitting optimization to improve the perceived fitting comfort of cyclists. Specific attention was given on how these modifications affected the seat pressure and the seat shear forces. It was hypothesized that 1) a reduction of shear forces applied by the cyclists on the saddle, and 2) the increase in peak pressure of sit bones attesting to better pelvic pose on the saddle will improve the perceived sitting comfort. Finally, it is hypothesized that 3) the width and the softness of the saddle would affect the pelvic pose on the saddle and the sitting comfort.

2. Material and Method

2.1. Participants

11 trained male and 1 women road cyclists and triathletes (age: 24.1 ± 7.4 years, height: 178.4 ± 6.9 cm; body mass: 67.8 ± 7.7 kg, body mass index: 21.3 ± 1.5) volunteered to participate in the study (Table 1).

Since this study aimed to investigate the effect of an improvement in sitting comfort, participants were recruited only if they reported a perceived sitting comfort during their training on their road bike inferior 7 on the 0-10 VAS comfort scale (0 No comfort – 10 Extremely strong comfort) (Kyung, Nussbaum, & Babski-Reeves, 2008). Before participating in the experiment, each rider provided written informed consent, and the study was conducted following the ethical principles of the Declaration of Helsinki (1983) and approved by the regional ethics committee.

2.2. Procedure

Each participant performed a one-day laboratory visit. They performed twice a cycling exercise composed of 4 blocks of 5 min at a rate of perceived exertion (RPE) of 4 on the Borg's CR10 scale (Borg, 1998) on a treadmill (Rodby RL 2700 E, Rodby, Sweden) with their road bicycle at different slopes (1, 3, 6 and 9%) (Figure 1). The treadmill speed was replicated after the fitting optimization. Between both treadmill exercises, a fitting optimization was performed to improve perceived sitting comfort while riding.

Table 1. Participants characteristics. Level was given according to the categorization adopted by the French triathlon and cycling federation.

Participant	Age (year)	Height (cm)	Weight (kg)	BMI	Gender	Practice	Level	Volume (hours/week)
1	25	170	58	20.1	Female	Triathlon	Amatory	6
2	25	184	79	23.3	Male	Cycling	Amatory	8
3	17	172	55	18.6	Male	Cycling	Junior	12
4	25	192	80	21.7	Male	Triathlon	Category 2	13
5	47	168	61	21.6	Male	Cycling	Amatory	10
6	20	177	62	19.8	Male	Cycling	Category 2	14
7	26	178	76	24.0	Male	Cycling	Amatory	8
8	19	187	71	20.3	Male	Cycling	Category 1	15
9	23	178	70	22.1	Male	Cycling	Category 1	16
10	20	172	66	22.3	Male	Cycling	Category 1	16
11	21	182	71	21.4	Male	Cycling	Category 2	10
12	21	181	65	19.8	Male	Cycling	Category 1	15

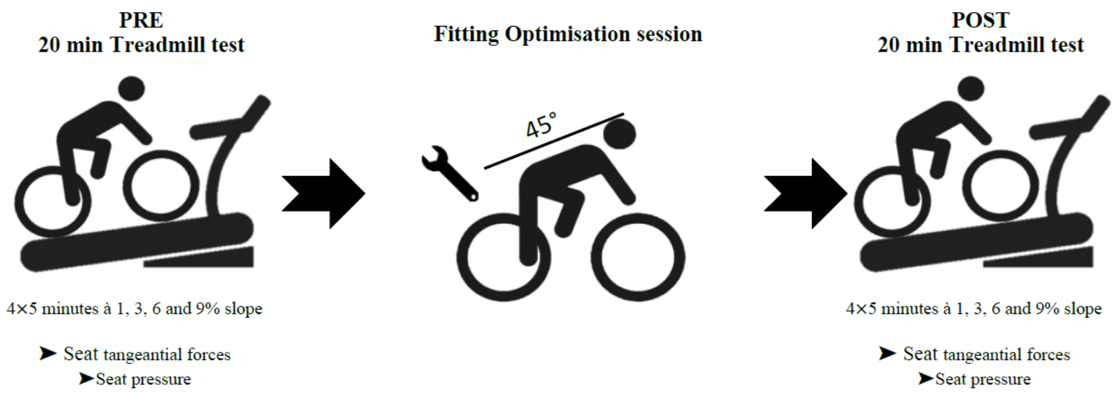

Figure 1. Design of the session performed by each participant. Each participant performed a 20 min treadmill exercise twice at different slopes. This treadmill exercise was composed of 4 blocks of 5 min at intensities of 4 on the CR10 Borg Scale. During each block, the saddle pressure and shear forces transmitted to the seat tube were measured. In-between both treadmill exercises, a fitting optimization was conducted to improve the participant's perceived comfort on their bicycle.

2.3. Treatmill test

Both 20 min treadmill tests were constituted of 4 consecutive blocks of 5 min performed at slopes of 1, 3, 6, and 9% respectively. At the beginning of each block, treadmill speed was adjusted until subjects rated their perceived exertion at 4 on the CR10's Borg scale. This intensity corresponds to an endurance cycling effort that is mainly produced by cyclists during their practice. Since not all participants had a powermeter, the power output was not measured during the test. During the last 30 s of each block, saddle pressure and shear forces were sampled using a saddle nap pressure system (GP BIKE, Gebiomized, Munster, Germany) and a homemade designed 4 components seat force sensor. After the completion of the treadmill exercise, participants had to rate their perceived comfort, in average during the 20min exercise, according to 10 items using a 0-10 VAS comfort scale (0 corresponds to very uncomfortable – 10 corresponds to very comfortable) (Kyung et al., 2008). These items related to the comfort perceived locally in different body regions which were hands, foot, upper and lower limbs, back, head; or items related to feeling on their bicycle like sitting, breathing, pedaling movement, and their general comfort.

2.4. Fitting optimization

The fitting session was performed on the subject's bicycle mounted on the Elite Direto trainer (Elite, Fontaniva, Italy). This session aimed to modify the position of the subjects and on their bicycle to improve their global and their sitting comfort. The bikefitting 3d motion analyzer camera and the bikefitting pedaling analyzer software were used (Bikefitting, Maastricht, Netherland) to record relevant joints angle of subjects while pedaling (Bouillod, Costes, Soto-Romero, Brunet, & Grappe, 2016). They were fixed on 7 anatomical landmarks which are the 5th metatarsal, external malleolus, heal, lateral femoral epicondyle, trochanter major, acromion, medial epicondyle humerus, and ulnar styloid process. While the 30-s dynamic fitting record, subjects had to maintain a RPE CR10 of 4 at a freely chosen CAD while they looked forward with their hands on the brake levers. Specific attention was paid to respect the recommendations in the maximal knee joint extension (Bini, Hume, & Kilding, 2014) (between 35 and 40°), the back angle (between and 39 and 45°) and the knee alignment with the pedal axis when pedal was at 90° (between -15 and 0 mm, 0° at 12 o'clock). Potential adjustments of saddle setback, saddle height and handlebar height were done according to the observations, the joint angle measurements, the bike fitting recommendations, and the ratings of subjects on the sitting comfort scale. Internal recommendations from the performance division of a world tour professional cycling team were also considered. These adjustments are described in Table 2. Changes in bicycle adjustments were stopped when participants rate the comfort of their position over 8 on the 0-10 VAS comfort scale. No duration was imposed to allow participant to be sure of their ratings. Thereafter, if participants perceived discomfort concerning their sitting, the saddle model and tilt were modified according to their feedback. Changes in saddle tilt and model were validated when participants rate the sitting comfort on the trainer over 8 on the 0-10 VAS comfort scale.

Before and after the fitting optimization procedure, 2d coordinates of the handlebar and saddle were measured. These measures were performed using a 2d bike adjuster, a saddle pointer tool, and a handlebar pointer tool (Bikefitting, Maastricht, Netherland). The 2d coordinates of the saddle peak, saddle center (where saddle width is 8 cm), and handlebar center (intersection between top spline of the stem cap and middle of handlebar) were measured in a 2d coordinate system whose origin is the center of the bottom bracket (Figure 2). Hence, the saddle height was calculated as the distance (in cm) between the bottom bracket and the middle saddle coordinate, and the saddle-to-handlebar drop (in cm) was measured as the difference between the vertical (y) coordinate of the middle saddle and handlebar center.

Moreover, some characteristics of the saddle model used during the fitting optimization were measured. Its hardness at 4 points and 4 dimensions was measured (Figure 3). The saddle width, saddle length, the saddle nose length and saddle nose width were measured with a caliper (Magnusson MS32, Magnusson, France). Moreover, saddle hardness at sit bone right and sit bone left by measured using a shore durometer (Walfront2n3sx1ghzr, Walfront, China) placed at mid-distance between the saddle nose and the middle of the saddle, on the right side and the left side respectively. This tool allows for measuring the hardness of a material (in shore), a high value in shore represents a very hard material. Moreover, the saddle hardness in the pubic bone area was measured as the mean hardness measured on the right and left sides, at the middle distance between the nose of the saddle and the middle of the saddle. The tilt of the saddle was also measured with the bikefitting saddle tool which is a flat surface to pose on the saddle and the bikefitting inclinometer (Bikefitting, Maastricht, Netherland).

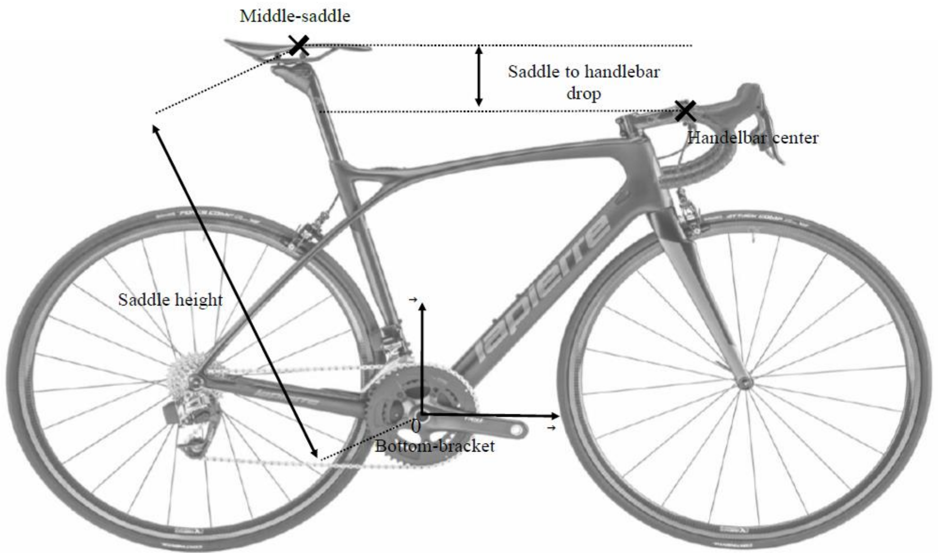

Figure 2. 2d coordinates of the middle-saddle (where saddle width is 8 cm), handlebar center (intersection between top spline of the stem cap and middle of handlebar) in a 2d coordinate system whose origin is the center of the bottom bracket. The determination of these coordinates allows the measurement of saddle height and saddle-to-handlebar drop.

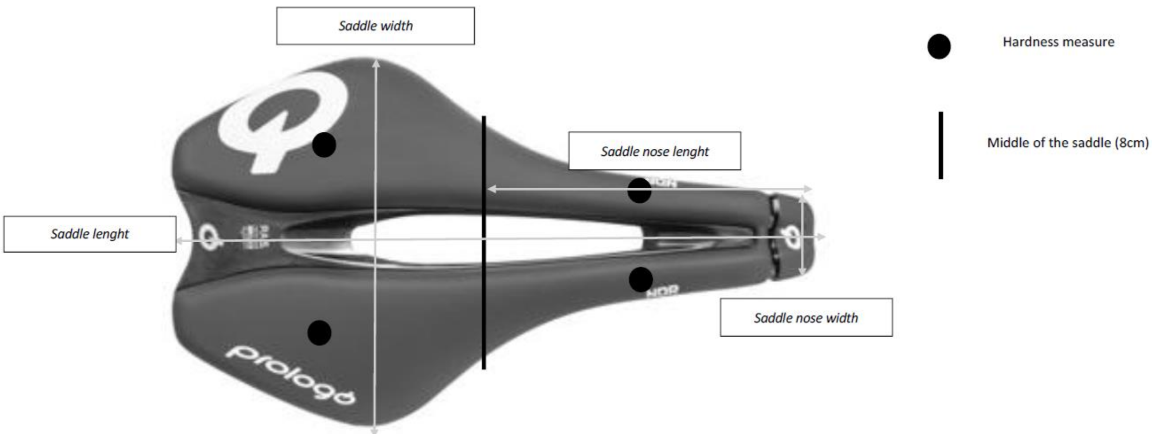

Figure 3. Characterization of the saddle. 4 dimensions (saddle length and width, saddle nose length and peak width) and hardness at 4 relevant points (middle of tip-middle and middle-peak saddle distance on both right and left sides) were measured.

2.5. Seat pressure measures

The saddle nap pressure system (GP BIKE, Gebiomized, Munster, Germany) allowed measuring the mean pressure (MPa), the peak pressure (MPa), and the loading surface (mm^2) over the entire contact surface between the buttocks and the saddle (Guiotto, Spolaor, Albani, & Sawacha, 2022). This surface is split into 3 zones corresponding to the area where the sit bone left, the sit bone right, and the pubic bone area is posed. Moreover, this tool measures the magnitude of displacement (in mm) of the cyclist's center of pressure on the saddle in anterior-posterior and lateral-medial directions (Figure 4).

Hence, during each slope on the treadmill test, mean pressure, peak pressure, and loading surface were measured at sit bone left, sit bone right, and pubic bone area. Moreover, the displacement in the anterior-posterior and lateral-medial direction of the cyclist's center of pressure was measured.

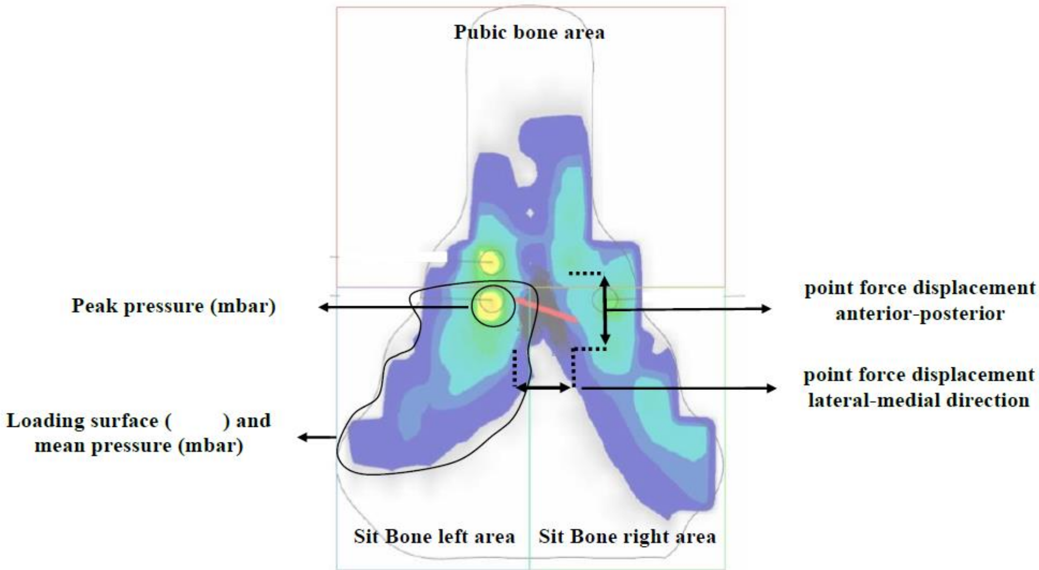

Figure 4. Topographical map of the saddle pressure illustrating the peak pressure, mean pressure, and loading 205 surface at sit bone left, sit bone right, and pubic bone area. This map also presents the point force-displacement in 206 anterior-posterior and lateral-medial direction. The system used is the GP BIKE saddle pressure system *(GP BIKE,* 207 *Gebiomized, Munster, Germany).*

2.6. Seat shear forces measures

The custom force sensor was constituted of 4 beams and connects the saddle with the seat tube (Figure 5). Two beams can be distorted in the anterior-posterior direction and two in the lateral-medial direction. Hence, this sensor would allow the measurements of forces and moments transmitted to the seat tube in the anterior-posterior and lateral-medial using the strain gauges placed on each beam. Tensions U_1, U_2, U_3, and U_4 measures by the 4 strain gauges were used to calculate shear forces and moments in anterior-posterior (Ft_x and M_x) and lateral-medial (Ft_y and M_y) directions. The calibration of this sensor was determined using the least square regression method that allows the combination of multiple loads during calibration (D'hondt, Dieltiens, & Juwet, 2018). The calibration matrix (K) was then obtained (Equation 2) and used to convert tensions into forces and moments (Equation 1). The 4 strain gauges signals were amplified by a shield (Wheatstone Amplifier Shield, RobotShop, Mirabel, Quebec, Canada) and processed using an Arduino UNO (Arduino Uno, Arduino.cc, Ivrea, Italy). A python custom program was developed to start/stop acquisition and export data into a .csv file. An internal validation of the seat shear forces sensor was conducted internally in the laboratory.

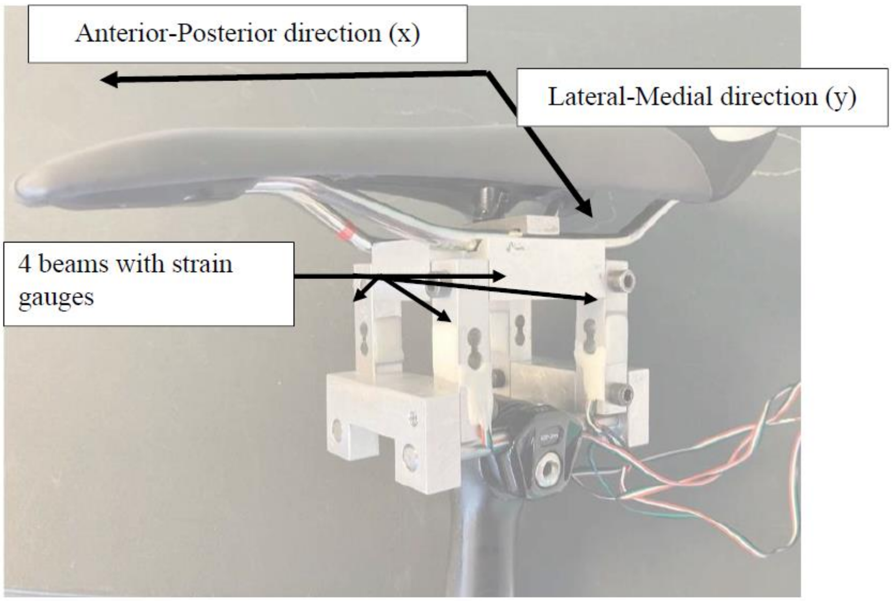

Figure 5. Seat force sensor composed of 4 beams with strain gauges which allow the measurement of forces transmitted to the seat tube in both anterior-posterior and lateral-medial directions.

$$\begin{bmatrix} Ft_x \\ Ft_y \\ M_x \\ M_y \end{bmatrix} = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} \cdot K \qquad [1]$$

$$K = \begin{bmatrix} a_{U_{1Fx}} & a_{U_{2Fx}} & a_{U_{3Fx}} & a_{U_{4Fx}} \\ a_{U_{1Fy}} & a_{U_{2Fy}} & a_{U_{3Fy}} & a_{U_{4Fy}} \\ a_{U_{1Mx}} & a_{U_{2Mx}} & a_{U_{3Mx}} & a_{U_{4Mx}} \\ a_{U_{1My}} & a_{U_{2My}} & a_{U_{3My}} & a_{U_{4My}} \end{bmatrix}^{-1^T} \qquad [2]$$

To quantify the amount of shear forces applied by the oscillations of the cyclists on the saddle, we calculate the ratio between the seat shear forces (in N) transmitted to the seat tube and the displacement of the cyclist's center of pressure on the saddle measured using the saddle pressure system, in both anterior-posterior and lateral-medial direction (Ft_x and Ft_y the shear forces (in N) in anterior-posterior and lateral-medial directions respectively, and x and y the displacement (in mm) of the cyclist's center of pressure in anterior-posterior and lateral-medial direction respectively). To quantify the shear forces generated by the oscillation of the cyclist's pelvic over the saddle during pedalling, $\frac{Ft_x}{x}$ and $\frac{Ft_y}{y}$ (in N·mm^{-1}) were calculated.

2.7. Statistical Analyses

A sample size calculation was performed with the G*Power software (Heinrich-HeineUniversität Düsseldorf, Düsseldorf, Germany) that adjusted for the ANOVA within factor test. Significance level (α) was fixed at 0.05, power (β) was fixed at 0.8 the effect size (ES) was fixed at 0.78. With this parameter, power analysis indicated that at least 12 participants were needed for this study. Hence, only effect size superior to 0.78 could be considered to interpret our data.

Statistical analyses were performed using R Studio (R Studio, Vienna, Austria). The Shapiro-Wilk statistical test revealed that all the data were normally distributed. A sphericity test was also performed with Mauchly's tests, and a Greenhouse-Geisser correction was applied if the sphericity was violated. If significant interactions were found *posthoc* Bonferonni tests were applied to examine significant differences between pairs of means. To investigate the differences between the seat forces, the seat shear forces, and the seat pressure variables measured before (PRE) and after (POST) the fitting optimization, during each slope (1, 3, 6, and 9%) of the treadmill test, a two-way repeated measure ANOVA

(Time * Slope) was conducted. To investigate the differences in perceived comfort between the whole PRE and POST treadmill tests, a one-way repeated measure ANOVA was conducted (Comfort). Effect sizes (ES) were calculated for each set of data (Cohen, 1988).

Finally, a correlation analysis was performed to analyse how the saddle characteristics and the handlebar-saddle drop prescribed after the fitting optimization test affects the seat pressure and forces measured during the treadmill test, on average for all slopes.

Cohen's d classification of effect size magnitude was used, whereby d < 0.2 = negligible effect; d = 0.2–0.49 = small effect; d = 0.50–0.8 = moderate effect and d > 0.8 = large effect.

3. Results

Mean ± SD values of the seat forces, seat shear forces and pressure measured during the treadmill test, on average for all slopes, PRE and POST the fitting optimization test are presented in Table 4.

The modification of the participant's bicycle settings and the characteristics of the saddle used during the fitting optimization are presented in Table 2 and 3.

Table 2. Modification of the participant's bicycle settings performed following the fitting optimization

Participant	Saddle height change (in mm)	Saddle set-back change (in mm)	Saddle tilt change (°)	Handlebar height change (in mm)
1	0	-8	-2.9	+21
2	-6	-7	-1.4	+6
3	+13	-4	-1.6	-28
4	+9	+40	+1.1	-8
5	-16	-42	+3.1	No change
6	-1	+6	+4.2	No change
7	+15	+34	+1.8	+3
8	+4	-3	+0.2	No change
9	+13	-25	-3.8	-11
10	+19	-23	-2.5	+9
11	-3	-5	-3.8	+5
12	-3	-37	+2.9	No change

Table 3. Hardness and dimensions characteristics of the participant's saddle used during the fitting optimization

Participant	Saddle model (Width x Length (in mm))	Saddle nose width (in mm)	Saddle nose length (in mm)	Hardness public bone (HA)	Hardness sits bone (HA)
1	272 x 136	42	169	78	64
2	277 x 130	40	140	63.5	53
3	273 x 142	42	151	61	53.5
4	242 x 143	46	118	64	61
5	251 x 137	38	135	56	55
6	251 x 137	38	135	56	55
7	142 x 143	46	118	64	61
8	251 x 137	38	135	56	55
9	270 x 141	44	153	65	82
10	270 x 133	41	169	56	55
11	251 x 137	38	135	67.5	66.5
12	270 x 133	42	169	64.5	67.5

Table 4. Seat forces, seat shear forces and pressure measured during the treadmill test, on average for all slopes, before (PRE) and after (POST) the fitting optimization test. Ft_x and Ft_y the forces in anterior posterior and lateral-medial directions respectively, and x and y are the displacement of the cyclist's center of pressure on the saddle in anterior-posterior and lateral-medial direction respectively. * P<.05

	PRE			POST		
	Sit bone left	Sit bone right	Public bone	Sit bone left	Sit bone right	Public bone
Mean pressure (mbar)	150 ± 70	148 ± 78	178 ± 78	167 ± 54	169 ± 40	177 ± 67
Peak pressure (mbar)	431 ± 181	485 ± 192	543 ± 206	514 ± 142*	588 ± 116*	586 ± 206
Loading surface (mm^2)	4823 ± 1684	4693 ± 845	5950 ± 738	5517 ± 926	5581 ± 848	5765 ± 760
x (mm)		34.7 ± 14.0			40.2 ± 8.3	
y (mm)		31.2 ± 19.7			38.1 ± 18.4	
Ft_x (N)		50.8 ± 17.5			53.6 ± 17.0	
Ft_y (N)		35.2 ± 19.9			34.2 ± 17.9	
Anterior-posterior shear forces ($N{\cdot}mm^{-1}$)		1.7 ± 0.8			1.5 ± 0.5	
Lateral-medial shear forces ($N{\cdot}mm^{-1}$)		1.7 ± 1.3			1.2 ± 0.9*	

Following the fitting optimization test, the perceived sitting comfort was significantly improved (+77 ± 131%, P<.01, d>0.8) (Figure 6). Moreover, the fitting optimization has a small effect on the general perceived comfort (+6 ± 12%, d>0.3).

Independently of the slopes imposed during the treadmill test, there was a significant decrease in lateral-medial shear forces (-32 ± 42%; F (1,10)=5.5, P<.001, d>0.8, Figure 8) and a significant increase in peak pressure at the sit bone right (+28 ± 83%; F (1,10)=10, P<.01, d>0.8, Figure 7) following the fitting optimization test. Furthermore, the fitting optimization test had a moderate effect on the peak pressure at the sit bone left (+19 ± 63%; F(1,10)=6, d>0.78).

The slope has a significant effect on the displacement of the cyclist's center of pressure in the lateral-medial direction (F(3,30)=6.6, P<.05) and on the loading surface at the sit bone right (F(3,30)=2.9, P<.05) but no statistical were reported in post-hoc tests.

No significant interaction Time*Slope was reported for the seat shear forces and pressure measured during the treadmill test.

Finally, a significant inverse correlation was reported between the saddle to handlebar drop and the saddle peak pressure at sit bone right (r=-0.79, P<.005) and sit bone left (r=-0.78, P<.005) measured on average during all slopes of the treadmill test. Furthermore, anterior-posterior shear forces are inversely correlated with the harness of the saddle at sit bone left (r=-0.71, P<.05) and sit bone right (r=-0.66, P<.05).

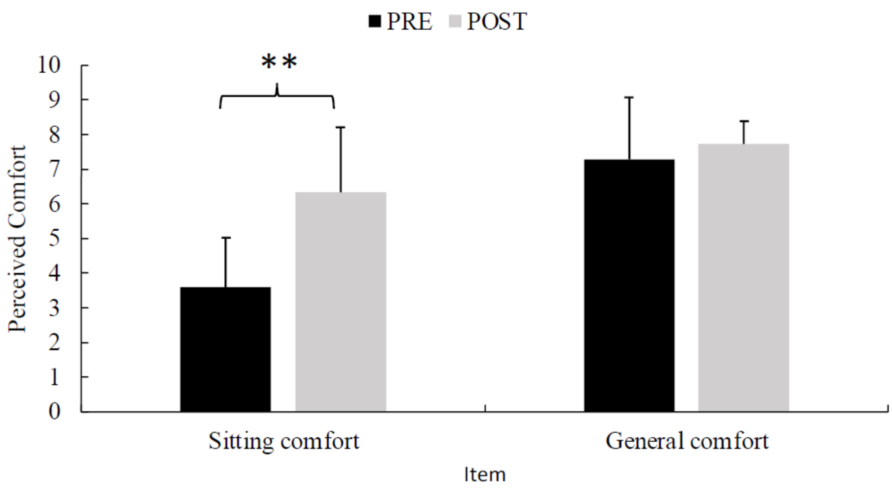

Figure 6. Perceived comfort in average for all slopes concerning the sitting and the general comfort on the bicycle before (PRE) and after (POST) the fitting optimization test. ** P<.01

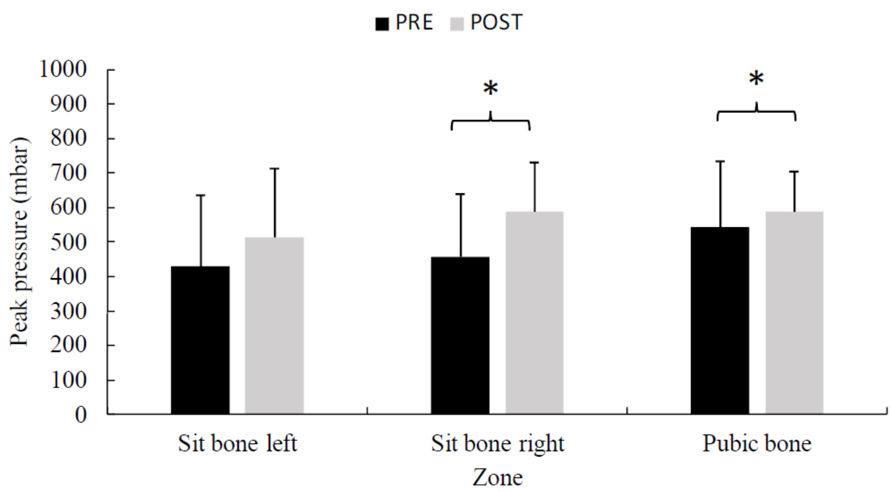

Figure 7. Saddle peak pressure at the sit bone left, the sit bone right and the pubic zone in average for all slopes measured during the treadmill test before (PRE) and after (POST) the fitting optimization test. * P<.05

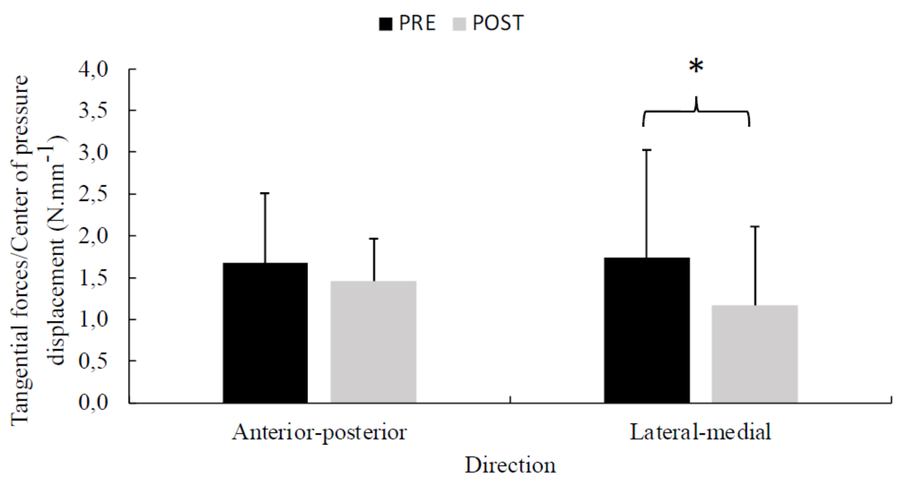

Figure 8. Ratio of the shear forces and the point application force-displacement in the anterior-posterior and lateral-medial direction in average for all slopes measured during the treadmill test before (PRE) and after (POST) the fitting optimization test. * P<.05

4. Discussion

The major result of this study is that the fitting optimization improved the perceived sitting comfort by 77%. It was hypothesised that a low degree of shear forces applied by the cyclists on the saddle, and the pressure mapping attesting to the pose of sit bones on the saddle will improve the perceived sitting comfort. The results of this study agreed with our hypotheses since the improvement in sitting comfort was associated with a reduction in medial-lateral shear forces applied on the saddle. Moreover, the increase in peak pressure at the sit bone left and right areas suggested a better pose of the sit bones on the saddle. Such improvement would be related to biomechanical sitting changes induced by the changes in the position and saddle model. In fact, the decrease in lateral-medial shear forces and the increase in peak pressure at sit bone left and right following the fitting optimization would be induced by better stability of the cyclist's pelvic on the saddle, therefore reducing the proportion of shear forces applied on the saddle during pedaling.

The increase in peak pressure at the sit bones left and right following the fitting optimization may be due to a better pose of the pelvic on the saddle. The lack of ischial tuberosities support by the saddle may increase the contact with soft tissues to support the cyclist's weight, therefore reducing peak pressure. Indeed, an adapted saddle should allow the support of ischial tuberosities to reduce the stress exerted on the perineum (Spears et al., 2003). Hence, this increase in peak pressure observed would be associated with a decrease in stress on genital tissues, therefore explaining partly the improvement in sitting comfort.

The forces applied on the saddle measured in our study of 53.6 ± 17 N in the anterior-posterior direction, and 34.2 ± 17.9 N in the lateral-medial direction represented around 8% and 5% of the participant's total weight (665.1 ± 75.5 N). This is in line with (Wilson & Bush, 2007) who reported that cyclists exerted shear forces in anterior-posterior and lateral medial-direction of 11-12% and 4-5% of their total body weight respectively, during a pedaling exercise at 125 W and 75 rpm. The potential higher power produced by our experts' participants would cause more reaction forces exerted by the pedal on the cyclist, therefore explaining the less important shear forces measured, especially in the anterior-posterior direction (11% versus 8%). Since the cyclist's pelvic is oscillating over the saddle during pedalling, it is hypothesised that shear forces are generated on the cyclist tissues in contact with the saddle. Shear forces were identified as a factor contributing to sitting comfort in everyday-life sitting situations (Goossens & Snijders, 1995). Indeed these forces led to frictions and distortions of the skin leading to pathologies such as occlusions or necrosis (Zhang et al., 1994). Hence, the significant reduction observed in lateral-medial shear forces would limit the friction and distortion on the cyclist's buttock tissues, therefore contributing to the improvement in sitting comfort.

The correlation analysis between the saddle to handlebar drop and the saddle peak pressure at sit bone right ($r=-0.79$, $P<.005$) and sit bone left ($r=-0.78$, $P<.005$) measured on average during all slopes of the treadmill test argued that the changes in the cyclist's position following the fitting optimization contributed to the increase in peak pressure at sit bone left and sit bone right. Indeed, the reduction on the saddle to handlebar drop increases the pressure in these areas. It is hypothesized that the reduction of drop encouraged a more open back angle accompanied by a pelvic retroversion, therefore increasing the peak pressure of the sit bone left and right. Some authors studied the impact of the position on penile oxygenation, which is mainly driven by the compression of the pudendal nerve. Gemery et al., (2007) reported that the compression sites of the pudendal nerve situated directly under the perineal area are compressed when the cyclists pelvic is more in anteversion. Moreover, during a 15 min exercise at 60-65% $\dot{V}O_2max$, the penile oxygenation is enhanced of 60% with a back angle of 90° compared to a back angle (Sommer, 2003). This may be caused by more compression at the pubic bone, favoring the compression of the pudendal nerve. In our study, the increase of the pressure at peak bone left and right would decrease the compression of the perineal area and positively contribute to the cyclist's sitting comfort.

Finally, the saddle hardness at sit bone left and right could also influence the degree of shear forces applied by the cyclist on the saddle. This was supported by the inverse correlation between the anterior-posterior shear forces and the harness of the saddle at sit bone left ($r=-0.71$, $P<.05$) and sit bone right ($r=-0.66$, $P<.05$). Hence, the harder the saddle at sit bone left and right, the lower anterior-posterior shear forces. This suggested that a soft saddle at sit bone left and right allowed fewer shear forces applied by the cyclist in the anterior-posterior direction. It suggests that softened material would improve the pelvic stability on the saddle, by improving the anchoring of the pelvic sit bone in the saddle. To our knowledge, no studies quantified the hardness of a saddle. However, this criterion is appreciated when customers choose their saddle.

6. Conclusions

This study is the first to report that seat pressure and shear forces applied by the cyclists on the saddle would impact their perceived sitting comfort by limiting the shear forces and stresses on sensitive tissues. Despite the morphological and flexibility differences among cyclists, universal factors like the handlebar to saddle drop and the saddle hardness of sit bones seemed to promote good pelvic stability on the saddle.

7. Implications

These results could have major interest to help bike-fitting practitioners in their data interpretation concerning the saddle-cyclist interface. Furthermore, it could indicate to saddle manufacturers important factors to consider in their saddle development. Indeed, the saddle must improve the pelvic stability that would limit the shear forces and pressure on sensitive tissues to allow a good sitting comfort. Some factors such as the dimension and the hardness are important to consider. Future investigation carried out on a larger sample and including a cohort of women are encouraged to confirm our results. Furthermore, a long-term follow-up on comfort, performance, and limitation of injuries could be relevant to reinforce the results.

8. Limitations

The adjustments implemented during the fitting optimization depend on the experimenter's analysis and interpretation of the objective and subjective measurements. Hence, this would influence the results obtained in this study.

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