No Effect of Cycling Shoe Outsole Stiffness On Sub- and Supra-Maximal Cycling Performance Parameters.

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TITLE PAGE

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No effect of cycling shoe outsole stiffness on sub- and supra-maximal cycling performance parameters.

BRIEF RUNNING HEAD:

Cycling shoe outsole stiffness and performance.

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ABSTRACT

Background: The aim of this study was to test the effects of cycling shoe outsole stiffness on both performance and comfort parameters during sub- and supra-maximal cycling tests.

Methods: Two groups of recreational women tested three cycling shoe conditions with differing outsole stiffness. One group of 8 women performed four cycling tests of 3 min composed of two intensities (100 and 140 W) and two pedaling rates (70 and 100 rpm) for each pair of shoes. Metabolic and subjective perception of comfort measurement was evaluated with each shoe. Another group of 12 women performed 6-s all-out sprints against two external

resistances (0.4 and 0.7 N/kg) to determine force-velocity relationships with the three cycling shoe conditions. **Results:** The main findings are that the stiffness of the investigated outsole cycling shoes (i) does not influence cycling performance whatever the test (ii) while the perception of comfort is largely degraded compared to the most flexible shoe. **Conclusion:** Maximizing stiffness should no longer be of the highest design principal for beginners or recreational women cyclists.

KEYWORDS: Efficiency; sprints; comfort; shoe–pedal interface; non-cyclists.

BACKGROUND

In cycling, the majority of the energy imparted to the bike occurs through the link between the foot and the crank through the shoe–pedal interface [1-2]. This interface allows the transmission of the force developed by the cyclist's lower limbs to the crank, and then to the chainring. The resultant force applied to the crank can be divided into an effective force perpendicular to the crank and directed in the direction of rotation, and ineffective forces parallel to the crank. Consequently, the shoe–pedal system influences both muscular force production and mechanical force effectiveness (ratio of effective force/resultant force), making it an essential interface. Improving the transmission of a force through an interface is possible by minimizing the loss of energy in the deformation of this interface. From a mechanical point of view, stiffness is the ability of a solid object to resist deformation when it is subjected to mechanical stresses. It mainly depends on the geometry and the elasticity modules of the material used. Contextualized to cycling, all the subcomponents constituting the shoe–pedal interface should thus be stiff, with the single purpose of transmitting force: the sole of the shoe as a support between the foot and the pedal, and the linkage of the shoe with the pedal [1-3].

The present study focuses only on the outsole of the shoe, i.e., the structural portion of the shoe that transfers the force.

There are many claims by cyclists and industry professionals about the advantages of outsole stiffness using composite materials (such as carbon fiber) that ensure stiffness while remaining light and thin. The study of Jarboe and Quesada [4] compared the influence of the stiffness of cycling shoe midsoles on plantar pressure during an exercise of 400 W at 90 rpm. Firstly, dynamic mechanical testing indicated that cycling shoes with carbon fiber composite midsoles were significantly stiffer than cycling shoes made with a more traditional plastic sole, in both longitudinal bending and three-point bending. They then showed that these stiffer cycling shoes induced peak plantar pressures 18% higher in the forefoot region (first metatarsal head and hallux) than did the other shoe with a plastic midsole. The limited ability to flex the metatarsophalangeal joint under load with a stiff sole, and thereby conform to foot contours so that loads may not be spread over larger areas, may explain this higher plantar pressure [4-5]. The plantar pressure increase is consistent with an optimization of pedaling kinetics, since this forefoot region was identified as the major force-contributing structure of the foot [5], and the relative contribution of this region increases with an increase of power output from 100 to 400 W [6].

The scientific literature showed that the increase in the longitudinal bending stiffness of sole athletic shoes results in an improvement in performance during maximal intensity short-term pushing movements, such as sprinting and jumping [7-10]. The causal mechanism is the reduction in the range of motion of the metatarsophalangeal joints, which reduces the amount of energy dissipation at this joint. One might hypothesize that stiffer-outsole cycling shoes also transfer power more efficiently to the crank, leading to better performance. It is difficult to answer this question correctly based strictly on the literature. On the one hand, the studies that tested large differences in shoe stiffness had to use running shoes for the minimum stiffness

condition [e.g. 6, 11-16]. But the running shoe inevitably requires the use of flat or toe-clip pedals, while the cycling shoes used to qualify stiffness require clipless pedals. Furthermore, the differences between running and cycling shoes were not only in terms of the stiffness of the outsole but also the thickness and width of foam between in- and outsole. Consequently, these studies cross the stiffness effect with the type of shoe–pedal linkage and/or other shoe characteristics. The results are thus highly variable depending on the equipment tested. On the other hand, some studies only use road cycling shoes with clipless pedals, investigating a spectrum of commercially available shoes with different longitudinal bending stiffness [17] or comparing standard insoles vs. carbon fiber insoles or a specific orthosis placed in the same road cycling shoe [5-18-20]. These two procedures have the advantage of only testing the stiffness effect, but the disadvantage of doing so in a low stiffness range, i.e., with very low stiffness differences between the shoe conditions. Indeed, all the commercially available road cycling shoes can already be characterized as stiff compared to other type of sports shoe, and only stiff to very stiff conditions are therefore compared when a full carbon fiber insole is added. Additional data presented in Hurt's thesis [21] confirm this limit: most of the subjects testing the spectrum of commercially available road shoes reported that all of the shoes felt similar, comfortable, and stiff enough for cycling sprinting, and they were not able to correctly guess the relative stiffness of each shoe. These studies reach a consensus: little or no effect of sole stiffness on parameters of cycling performance. Hurt and Kram [17] and Koch et al. [20] showed that increased longitudinal bending stiffness of cycling shoe soles had no effect on sprint performance during short uphill sprints and 20-s Wingate anaerobic power test, respectively. Moreover, Anderson and Sockler [18] found that, at a given mechanical power output, there were no statistically significant differences in oxygen consumption, expired ventilatory volume, or heart rate between the conditions with/without foot stiffness orthoses. Fletcher et al. [19] complemented this analysis by testing the torsional stiffness of the road

shoes during sub-maximal cycling. They did not find any statistically significant differences between either the knee moment or the gross efficiency in the two stiffness conditions. To conclude, the cycling outsole shoe stiffness can affect pedaling kinetics [4] without affecting performance parameters in both supra- and sub-maximal conditions [17-20].

This result is encouraging in terms of reducing foot pathology, since there are negative consequences to high stiffness. Firstly, the repetitively occurring high pressure under the forefoot attained with the stiffer outsole may be the cause of localized ischemia, paresthesia, and metatarsalgia syndromes of the forefoot frequently observed in cyclists [1, 3-5, 22-28]. Secondly, if a stiff sole transfers forces more efficiently, it also transfers more vibrations. Vibrations can also cause musculoskeletal disorders [29]. Ultimately, both high plantar pressure and vibration transmission also affect comfort [3, 30-31]. A shoe that flexes more to conform to foot contours, and that dampens vibration over rough terrain, is theorized to be a more comfortable and “safer” shoe.

To optimize both cycling performance and shoe comfort, investigations are needed to clarify which optimal value of outsole stiffness is required. Thus, it would be necessary to test a large range of outsole cycling shoe stiffnesses in different power output conditions. Moreover, women are too little studied in cycling literature, and the results of studies obtained on men cannot be completely extrapolated to women, particularly with regard to mechanical data of mass, stiffness, and power. For example, the maximum power developed during sprinting is 500–800 W in high-level women cyclists [32] vs. 1100–1400 W in men [33-34]. Consequently, women cyclists may exert less pressure on the outsole, which would deform it to a lesser degree, compared to male cyclists. Sole stiffness is probably even less important in women, since they are generally less powerful. It is relevant to focus on the influence of shoe stiffness in woman cyclists on both performance and comfort by testing a wide spectrum of outsole stiffnesses greater than those offered by commercially available cycling shoes.

The aim of this study was thus to test the effects of cycling shoe outsole stiffness on both performance and comfort during sub- and supra-maximal cycling tests in women. The performance was quantified by the external force production capacities (Force-Velocity-Power relationship) for the supra-maximal test, and by energetical and perceptual parameters for the sub-maximal test. It was expected that the shoe stiffness should be adapted to the power output: no effect during the sub-maximal test since the power output is very low, but a possible decrease of some mechanical parameter developed during the sprint with the more flexible outsole. A second hypothesis was that the too stiff outsole lead to perceived discomfort.

MATERIAL AND METHODS

Main characteristics of the shoes tested

Three cycling shoe conditions were tested with highly different outsole stiffnesses: very low, moderate, and high, respectively named S–, S, S+. The stiffness was qualified by the type of outsole materials and their density and was quantified by material testing techniques using certified procedures (resistance at rupture, modulus of elasticity, and elongation at rupture index; Table 1). This dynamic shoe testing showed that the S+ shoe was stiffer than the S and S– shoes irrespective of the test, and that, inversely, the S– shoe was very flexible. To illustrate this difference in stiffness in practical terms, the S– shoe can be deformed so as to fold the shoe back on itself (toe–heel contact) with the force of a single hand.

Table 1: Mean mechanical characteristics of the shoes tested.

	S–	S	S+
Outsole material	Polyamide	Thermoplastic + 5% fiberglass	Full carbon
Density g/cm ³	1.14	1.23	1.78

Resistance at rupture by traction (da N/mm ²)	6	14.5	415
Resistance at rupture by flexion (da N/mm ²)	5.5	13.8	-
Modulus of elasticity by traction (da N/mm ²)	180	4960	23100
Modulus of elasticity by flexion (da N/mm ²)	140	276	-
Elongation at rupture by traction (%)	200	>10	1.8

Legend: Shoe stiffness measurements were collected under controlled conditions and in two different configurations using dynamic hydraulic tensile testing machines.

The three pairs of cycling shoes were manufactured by Mavic SAS (Annecy, France) in the same size (European size 38^{1/3}), modifying only the material used in the outsole of a shoe model available on the market (Ksyrium Elite W). Consequently, the three shoes were identical except for the outsole material and, thus, longitudinal bending stiffnesses. However, it should be noted that the color of the outsole differed: S+: black; S and S-: white. These three outsole stiffness conditions were tested in both sub- and supra-maximal cycling situations during two independent studies (two protocols and two different populations). The participants were blinded to the outsole characteristics.

Sub-maximal exercise:

Participants:

Eight women (age 21.3 ± 1.8 years, height 164.4 ± 5.4 cm, weight 57.5 ± 5 kg) participated in this study. They were physically active in different endurance sport activities, but none was specifically trained in cycling. However, they can be qualified as recreational cyclists because all have all ridden on various occasions. All participants were free of musculoskeletal pain or injury during the study. In addition, all provided written informed consent, and the local ethics committee approved both sub and supra-maximal protocols.

Experimental protocol:

The sub-maximal tests were carried out during a single laboratory session. Each participant warmed-up and familiarized themselves with the cycle ergometer for 10 min at self-selected sub-maximal intensity with the S shoe. After 5 min of passive rest, they performed, for each pair of shoes, four cycling tests of 3 min composed of two intensities (100 and 140 W) and two pedaling rates (70 and 100 rpm), i.e., 12 conditions for a total duration of 36 min. The order of shoe conditions was randomized and counterbalanced, and 5 min of active rest was imposed between the shoe conditions. For a shoe condition, the order of intensity and pedaling rate was also randomized and counterbalanced, without a rest period between conditions. Participants remained seated with both hands on the tops of the cycle ergometer handlebars, and they were obliged to maintain the imposed pedaling rate given through visual feedback.

Data collection and data analysis:

A standard friction loaded cycle ergometer (Monark type 818 E, Stockholm, Sweden) with clip-in pedals (ZXellium, Mavic, France) and circular chainring (Shimano XTR, France, 44 teeth) was used.

Metabolic measurement was performed with a portable breath-by-breath device (Cosmed K4b², Rome, Italy) throughout the entire test. Two-point calibration of the metabolic measurement system was performed prior to each session using room air and a gas mixture of known composition (5% CO₂, 16% O₂). Expired volume was calibrated using a 3-L syringe. Oxygen

consumption ($\dot{V}O_2$) was averaged during the last 60 s of each condition of 3 min at a steady state and expressed in $\text{ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$.

The perception of comfort felt with each shoe was evaluated after use of the shoe during the rest period. A visual analogue scale (VAS, 10 cm) from 0 (very uncomfortable or no discomfort) to 10 (very comfortable or unbearable pain) was used [35].

Statistical analysis:

All data are presented as mean $\pm$ standard deviation (SD). Distribution normality and sphericity were tested with Shapiro–Wilk’s and Mauchly’s test, respectively. When sphericity was not respected, the Greenhouse–Geisser correction was applied. Comfort data did not follow normality, a nonparametric Friedman test was then performed on each cycling condition to test the shoe effect. The $\dot{V}O_2$ data followed normality and respected sphericity. Then, two-factor repeated-measures ANOVA (shoe and intensity) for each pedaling rate (70 and 100 rpm) was performed, and Holm’s post hoc test was used to highlight significant differences between conditions. The magnitude of the observed differences across shoes was quantified using effect size statistics (ESs, Cohen’s d), with the thresholds for small, moderate, and large effects being set at 0.2, 0.5, and 0.8, respectively, and with 95% confidence intervals [CI] around the effect sizes [36]. For all statistical analyses, an alpha value of 0.05 was accepted as the level of significance. The data were processed in Excel and the statistical analyses in JASP.

Supra-maximal study:

Participants:

A total of 12 women (age 20 ± 1.8 years, height 165.5 ± 4.1 cm, weight 60.9 ± 6.4 kg) participated in the study. All specificities and information are similar to the sub-maximal study.

Experimental protocol:

The supra-maximal tests were carried out during a single laboratory session. Each participant performed a 15-min warm-up protocol with the S shoe (self-selected sub-maximal intensity for 10 min, then acceleration of 15 s) followed by 5 min of passive rest before the start of the force–velocity test. This test consisted of six all-out sprints of 6 s each, interspersed with 4-min rest periods. Each sprint was differentiated by the shoe condition (S+, S and S–) and by the external resistances applied to the flywheel (0.4 N/kg and 0.7 N/kg of body weight). The six sprints were performed in randomized and counterbalanced order. The start position was standardized with the crank of the right pedal still at 45° after the top dead center. At a signal given by the experimenter, participants were asked to pedal as fast as possible, that is, to produce the highest explosive force on the pedal, until told to stop. They were also instructed to stay seated on the saddle during the whole test. The experimenters vigorously encouraged the participants throughout the duration of each sprint.

Data collection and data analysis:

A standard friction loaded cycle ergometer (Monark type 818 E, Stockholm, Sweden) with clip-in pedals (ZXellium, Mavic, France) and circular plate (Shimano XTR, France, 44 teeth) was specifically equipped with an optical encoder (Hengstler type, RIS IP50, Aldingen, Germany) for the measurement of instantaneous flywheel displacement, and a strain gauge (typical MFG interface, Scottsdale, AZ, United States) for measurement of the instantaneous frictional force applied by the belt to the flywheel (for more detail, see 37). The saddle height was adjusted to individual anthropometric characteristics [38].

The pre-processed data averaged over each pedal downstroke (friction force (N), friction power (W), displacement (m), time (s), and velocity ($\text{m}\cdot\text{s}^{-1}$)) were sampled at 200 Hz and stored on a PC via software Sprint bicycle and a 12-bit analog-to-digital interface card. The first pedal stroke was deleted, since it was incomplete. The speed was smoothed using a 50-ms moving averaging window. First order derivatives of the velocity were calculated to obtain flywheel acceleration.

The inertia constant (13.4 N) was added to the acceleration to determine the inertia force. Both inertia force and mechanical resistance (0.2 N) were added to the friction force measured by the belt to determine the total force. Only one force–velocity relationship per participant and per shoe was determined by mixing the data of the two external resistances [37].

Six mechanical parameters were calculated per linear force–velocity relationship: F_0 and V_0 (respectively, theoretical maximum force at zero velocity and theoretical maximum velocity at zero force), P_{max} (theoretical maximum power in $W \cdot kg^{-1}$) corresponding to $0.25F_0V_0$ [39], F_{opt} (optimal force at P_{max} : $0.5F_0$), V_{opt} (optimal speed at P_{max} : $0.5V_0$), and the average force obtained at the first entire pedal downstroke (F_1).

Statistical analysis:

All data are presented as mean $\pm$ SD. All parameters followed normality distribution (Shapiro–Wilk test). When sphericity was not respected, the Greenhouse–Geisser correction was applied. One-factor repeated-measure ANOVA was performed to detect significant shoe effects, and Holm’s post hoc test was used to highlight significant differences between conditions. The magnitude of the observed differences across shoes was quantified using effect size statistics (ESs, Cohen’s d), with the thresholds for small, moderate, and large effects being set at 0.2, 0.5, and 0.8, respectively, and with 95% confidence intervals [CI] around the effect sizes [36]. For all statistical analyses, an alpha value of 0.05 was accepted as the level of significance. The data were processed in Excel and the statistical analyses in JASP.

RESULTS

Sub-maximal study:

Table 2 presents VAS perceived comfort and $\dot{V}O_2$ data for each shoe and each cycling condition. Results from the nonparametric Friedman test revealed no significant outsole stiffness effect on the perceived comfort, but an important tendency ($p=0.066$). Cohen’s d and

95%CI showed a large effect (-1.04 [-1.91;-0.18]) between S- and S+ outsoles and a moderate effect (-0.61 [-1.4;0.14]) between S- and S: the less stiff sole S- is perceived to be more comfortable than the stiffer soles S+ and S. On the other hand, the effect between S and S+ is small. $\dot{V}O_2$ is not significantly influenced by the shoe condition (p from 0.12 to 0.72) or by a cross shoe-intensity effect ($p = 0.67$), and Cohen's d are between 0.04 and 0.49, i.e. negligible to small.

Table 2: Values of perception of comfort and $\dot{V}O_2$ with each shoe for each cycling condition.

		S-	S	S+
Confort Scale (0-10)		1.15 ± 1.46	2.10 ± 1.83	2.99 ± 2.23
$\dot{V}O_2$ (ml.min ⁻¹ .kg ⁻¹)	70rpm/100W	30.9 ± 2.75	31.9 ± 1.38	31.7 ± 2.07
	70rpm/140W	35.6 ± 2.76	35.9 ± 2.16	35.7 ± 1.95
	100rpm/100W	36.8 ± 1.92	38.0 ± 3.19	37.4 ± 1.50
	100rpm/140W	39.7 ± 2.53	40.2 ± 3.30	40.0 ± 2.02

Legend: S-, S, and S+ corresponded, respectively, to the lowest, moderate, and highest stiffness of the outsole. Data are means ± SD.

Supra-maximal study:

The mechanical parameters obtained with each shoe are presented in Table 3. Statistical analysis did not show any significant shoe effect for all mechanical parameters (p from 0.26 to 0.86), and Cohen's d are between 0.01 and 0.26, i.e. negligible to small.

Table 3: Values of mechanical parameters measured during the sprints with each shoe.

	S-	S	S+
V0 (rpm)	225 ± 17.3	222 ± 21.1	221 ± 18.1
Vopt (rpm)	112 ± 8.67	111 ± 10.5	110 ± 9.04
F0 (N)	106 ± 11.88	107 ± 16.2	109 ± 14.1
Fopt (N)	53.1 ± 5.94	53.7 ± 8.08	54.7 ± 7.03
Pmax (W/kg)	9.86 ± 1.38	9.81 ± 1.40	9.97 ± 1.47
F1 (N)	83.3 ± 9.34	83.3 ± 10.7	83.1 ± 9.10

Legend: S-, S, and S+ corresponded, respectively, to the lowest, moderate, and highest stiffness of the outsole. Data are means ± SD.

DISCUSSION

The main finding of this study was that the stiffness of the tested outsole cycling shoes does not influence beginner or recreational women cycling performance investigated through oxygen consumption during submaximal exercise and external force capacities during supra-maximal tests.

This result is not surprising regarding the comparison between the two stiffest shoes of the three tested (S+ vs. S). These two shoes are marketed by a manufacture, the S shoe for leisure cyclists and the S+ for competitive cyclists. Thus, both have the same invariable characteristic of a road cycling shoe of being stiff, the S+ shoe being stiffer than the S shoe. No study has shown an effect for the stiffness of commercially available in- and/or outsoles in road cycling shoes on performance parameters during sprinting or sub-maximal tests [17-20]. Since these studies test male cyclists developing high levels of power, it is not surprising that the effect of lack of stiffness is also observed in our non-cycling women developing low power levels. Stiffness been the capacity of the support to deform or not under the application of a

mechanical stress, the low power developed by the women in this study does not allow a discrimination of the effect of the stiffness between the S+ and S outsoles tested. Alone this result is interesting, since it shows that women beginner or recreational cyclists can use road cycling shoes marketed to be less rigid, while maintaining the same level of performance as other more rigid shoes. However, cycling shoes with a higher bending stiffness have been shown to generate more discomfort and potentially aggravate metatarsalgia or ischemic syndromes due to the higher peak plantar pressure on the forefoot [1, 3-5, 22-28]. Consequently, testing commercial road cycling shoes has the advantage of providing cyclists with usable results on the balance between performance and foot pathology. However, this procedure also presents the disadvantage of testing a restricted range of stiffness, i.e., from stiff to very stiff. This limit was introduced by Hurt and Kram [17], who suggest carrying out a new study to investigate the cycling shoe sole stiffness at which sprint performance begins to diminish. In practical terms, it would be necessary to test shoes with mechanical characteristics of stiffness between that of a running shoe and that of a nylon outsole road cycling shoe

The present S- shoe responds to this characteristic: retaining all the specificities of a road cycling shoe (shoe-pedal linkage, shape, tightening), while reducing the stiffness of the outsole as much as possible. The present prototype makes it feasible to provide the most flexible road cycling shoe possible while maintaining the invariants of pedaling. It could be referred to as a flexible “slipper” road cycling shoe, i.e., with a very low resistance to deformation. A major result of this study was that the low longitudinal bending stiffness of the S- outsole had no effect on sprint performance in present women. Our results may be counterintuitive in view of the literature on the testing of flexible shoes. Burns and Kram [12] compared two extreme shoe types -highly flexible running shoes and carbon-soled cycling shoes- and showed that the flexible shoe decreases 100-m sprint performance in men. However, it seems problematic to conclude that the stiffness of these shoe is the only factor responsible for improving

performance, since both conditions proposed different pedal linkage. Moreover, the subjects were male cyclists who develop high power levels, therefore overly high mechanical stress compared to the low resistance to deformation of their flexible running shoe.

Thus, it seems that the resistance to deformation of the current S– flexible outsole is sufficient for the low maximal power output attained by the women tested (about 600 W). An analysis of pedaling kinetics supports and complements this hypothesis. The resultant force vector applied by the lower limb passes mostly to the metatarsophalangeal joint, directly over the pedal axis, as shown by the plantar pressure studies [5-6]. The longitudinal bending stiffness of the outsole over its entire length therefore has little or no influence. The only important area of the outsole is thus the surface just above the pedal. The clip-in pedals form a small rigid block under this joint, making it an almost non-deformable support during the pushing cycle phase. Thus, even if the S– outsole has a low longitudinal bending stiffness, it remains thin and therefore not vertically deformable. Consequently, the stiffness of the outsole in its entirety has no influence on maximal cycling performance, provided that it remains non-deformable precisely at the junction with the pedal.

These kinetic explanations also support the non-effect of outsole stiffness observed during the sub-maximal tests, the powers imposed being very low at 100 and 140 W. Since the outsole was not deformed by the application of the force produced by the women for these low constraints, it is logical that the oxygen consumption is significantly influenced by the outsole stiffness, irrespective of power or pedaling rate sessions. Our result agrees with those of other studies (i) comparing different stiffness insoles placed in road cycling shoes [18-19] and also (ii) comparing running shoes with road cycling shoes [14-16]. Only the studies by Jorge and Hull [40] and Cruz and Bankoff [13], to my knowledge, have shown conflicting results on EMG: soft-soled shoes (running or tennis shoes) required more leg muscle activity (quadriceps,

hamstrings) than soft-soled shoes. However, the pedal linkages are different, which is the purpose of these two studies.

The lack of effect of outsole stiffness on both supra- and sub-maximal cycling performance allows other important parameters in cycling to be considered: comfort and pathology. A tendency effect of stiffness was shown on the perceived comfort and a significant difference appears when comparing the two most distant outsoles in stiffness with a Holm's post hoc test. The less stiff outsole S- is perceived to be more comfortable than the stiffer outsole S+, with this effect being identified as large by the Cohen's d test. The explanatory hypotheses may be better plantar pressure distribution on a large part of the sole or lower peak plantar pressure with the less stiff outsole. This notion of perceived comfort is an important parameter for training and/or performance. The effect of outsole stiffness on perceived comfort during a cycling test is evaluated for the first time by the present study. Uden et al. [30] showed from a questionnaire that an overly stiff cycling shoe creates discomfort, given that 54% of the cyclists questioned felt foot pain with their stiff shoes. In fact, it is the link between comfort and pathology that this study questioned. There is a consensus that decreasing the stiffness of cycling shoe soles may help to prevent or alleviate the ischemia, paresthesia, or metatarsalgia that can occur in cyclists [1, 3-5, 22-28]. Thus, evaluating both performance and comfort seems to be the best solution to guide cyclists in choosing the best shoe for them. For the women in the present study, the best outsole maybe the less stiff, since it does not deteriorate their cycling performance and improves their perceived comfort, irrespective of the power output.

This recommendation cannot be strictly applied to male cyclists or elite women cyclists, i.e., cyclists developing high power output, which would thus deform the soles to a greater degree. However, it would be interesting to adapt cycling shoe stiffness to the power developed by those wearing them, in order to determine an optimal ratio of performance to shoe comfort. The hypothesis that different cyclists would require different shoe stiffnesses for their maximal

performance can also be supported. One could also argue that the stiffness for racing shoes should be different from that for training shoes, given the length of time required on the bike for elite cyclists to train. Using substantially less stiff cycling shoes during training would theoretically reduce the risk of foot pathologies and improve comfort. Finally, this study may also help manufacturers to improve the design of road cycling shoes by no longer focusing solely on this stiffness criterion.

CONCLUSIONS

To conclude, the stiffness of the outsole cycling shoes investigated does not influence current parameters of performance during sub- and supra-maximal tests in women. Similar results had been shown on cyclists during short uphill sprints [17], 20-s Wingate anaerobic power test [20] or submaximal cycling session [18-19]. This result is interesting since it shows that beginners or recreational women cyclists can use road cycling shoes marketed as being less rigid, while maintaining the same level of performance as other more rigid shoes. Cycling shoe outsoles can ultimately be optimized for comfort and injury prevention, as well as high performance. Further studies are needed to compare these results with other populations, such as competitive women cyclists who develop more power output, and other conditions, e.g., different gradients.

LISTE OF ABBREVIATIONS

S-: very low stiffness outsole; S: moderate stiffness outsole; S+: high stiffness outsole; $\dot{V}O_2$: Oxygen consumption; VAS: visual analogue scale; SD : standard deviation; ANOVA: analysis of variance ; ESs: effect size statistics ; CI: confidence intervals; F0: theoretical maximum force at zero velocity; V0: theoretical maximum velocity at zero force; Pmax : theoretical maximum

power; Fopt: optimal force at Pmax; Vopt: optimal speed at Pmax; F1: average force obtained at the first entire pedal downstroke.

DECLARATIONS

Ethics approval and consent to participate:

Ethical permission to undertake this work was granted by the University of Savoie Mont-Blanc.

All participants consented to take part in this research and for the findings to be published.

Consent for publication:

Consent to publish research findings was obtained from all participants prior to their participation in this project. No personal identifiable data is included within this publication.

Availability of data and materials:

All data can be made available from the corresponding author upon reasonable request.

Competing interests:

The authors declare no conflicts of interest.

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Authors' contributions:

All authors contributed to the design, registration, conduct and reporting of this research. All authors read and approved the final manuscript.

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