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Longitudinal bending stiffness of cycling footwear - What is stiff enough?

Stefan Litzenberger [1,*], Duc-Minh Tran [1] and Frank I. Michel [2,3]

1 Affiliation 1; University of Applied Sciences Technikum Wien, Department of Sports Engineering, Biomechanics & Ergonomics, Vienna, Austria. litzenberger@technikum-wien.at
2 Affiliation 2; *i-lab*, VAUDE Sport GmbH & Co. KG, Obereisenbach, Germany. frank.michel@vaude.com
3 Affiliation 3; SCM – Sports Consulting Michel, Langenargen, Germany. f.michel@sports-consulting-michel.com

* Correspondence: (SL) litzenberger@technikum-wien.at.

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Abstract: To investigate the influence of a cycling shoe's longitudinal bending stiffness on the kinematics of the cyclist's foot, three identical leisure-cycling shoes for flat pedals with different longitudinal bending stiffness were tested during indoor trials with twelve male subjects riding at five intensities in seated and standing cycling, respectively. Using an infrared-based 3D motion capture system and power output measurement with a crank-based power meter it was shown that power output does not differ significantly between shoes with different sole stiffness, that metatarsophalangeal angle between forefoot and rearfoot is increasing with increasing power and mostly decreasing with increasing bending stiffness of the shoe and that the pedal angle over crank-cycle shows individual differences that can be clustered in three types. Ultimately it can be said that Ethylenvinylacetat (EVA) inlays show excessive bending whereas there is only a small difference between nylon and nylon-carbon inlays.

Keywords: footwear; bicycling; biomechanics; longitudinal stiffness

1. Introduction

Whereas most sportive cyclists prefer stiff cycling shoe soles made of carbon and clipless pedals for riding, many leisure-time cyclists use flat pedals and sneaker style shoes to also ensure good performance and comfort while walking. The reasons can be manyfold and mainly include riders who: commute, bike and hike, use bicycles in a tourist or cultural scenario or do MTB-Enduro riding where carrying and riding technical downhills is an integral part.

Research has shown that increased longitudinal bending stiffness of the cycling shoe soles minimises deflection - and hence the foot's metatarsophalangeal angle (MTP) - of the cycling shoe during pedalling, thus reducing material deformation and increasing power-transfer (Burns & Kram, 2020; Davis & Hull, 1981; Gregor & Wheeler, 1994; Straw & Kram, 2016), ultimately leading to a higher performance.

The objective of this work is to investigate whether longitudinal bending stiffness of flat pedal cycling shoes as well as the load intensity has an influence on the MTP- and the pedal-angle and hence which stiffness is required to provide sufficient force transmission and still allow enough flexibility for walking.

2. Materials and Methods

Twelve healthy male experienced hobby cyclists (age: 27.2 ± 2.6 yrs., weight: 72.3 ± 6.3 kg, height: 176.8 ± 5.2 cm) participated in the study. Prior to the tests the subjects provided written informed consent and the study was conducted in accordance with the declaration of Helsinki.

All tests were done on a cyclocross bicycle (Merida Cyclocross 2017 54“, Merida Industry Co., Yuanlin, Taiwan) mounted on an Tacx indoor trainer (Neo Smart, Tacx Int BV, Wassenaar, The Netherlands). Power and cadence were recorded using a Rotor 2INPOWER DM ROAD power meter (170mm, Rotor Componentes Tecnologicos, S.L., Madrid, Spain, 200Hz) and a Garmin Edge 530 head unit (Garmin Ltd., Boulder, Colorado, USA). Flat pedal adapter plates were mounted on the pedals for use with flat pedal shoes.

Saddle height was individually adapted using 96% of floor to trochanter major distance during upright stance of each subject. Subjects had time to familiarise with the equipment and were then asked to perform five trials with three different shoes in randomised order at a cadence of 80 rpm with four different gear ratios and hence pedalling intensities (I1: 50x22, I2: 50x20, I3: 50x18, I4: 50x16) and an all-out standing start sprint until 80 rpm were reached (gear ratio 50x16 (I5)).

The three shoes (all EU-size 42) were three identical flat pedal prototypes of the company Vaude (Tettnang, Germany) with different midsole inlays (DF1: Ethylenvinylacetat (EVA) - soft; DF2: nylon - stiffer; DF3: nylon-carbon - stiffest).

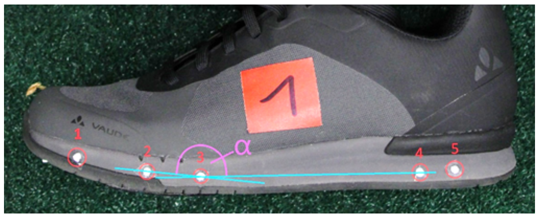

Figure 2. Test shoe with markers and the MTP-angle (α).

Five retroreflective hemispherical markers (⌀=3mm) were attached to the lateral midsole of the left shoe for motion capturing with an eight camera Vicon Nexus infrared 3D motion capture system (Vicon Motion Systems Ltd, Oxford, UK, 100Hz) and the subsequent calculation of the angles of interest. For each shoe first a calibration measurement was done to determine a possible offset and second for each trial 30s of motion were captured and ten continuous steady-state crank revolutions were extracted. Data were processed using Matlab2021a (The MathWorks, Inc., Natick, Massachusetts, USA) to separate single crank-cycles, and calculate MTP- and pedal angle as well as their maxima. A 2-way ANOVA was conducted for statistical evaluation.

3. Results

As expected the maximum MTP-plantarflexion as well as the maximum angle occurred in the first two quadrants of the crank cycle (45°-225°). It could be shown that MTP-plantarflexion for each shoe increased with increasing load and decreased with increasing stiffness of the shoe (all: $p<0.01$) (Figure 3). Throughout the crank-cycle only MTP-plantarflexion but no MTP-dorsiflexion occurred. The mean course of the bending angle (α) is depicted in Figure 4, power output for each intensity is found in Table 1.

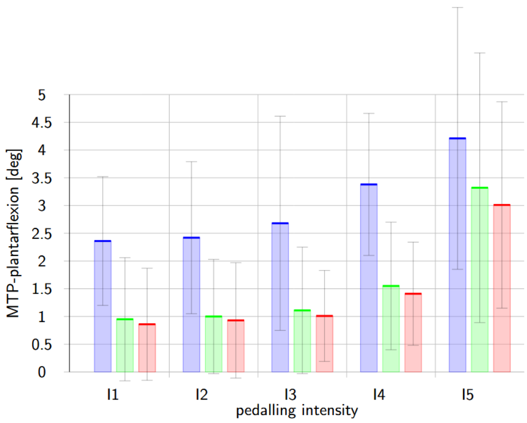

Figure 3. Mean maximal (± SD) MTP angle (α) in Q1 and Q2 (45°-225°) for the five pedalling intensities (I1...I5) for all shoes (blue: DF1, green: DF2, red: DF3).

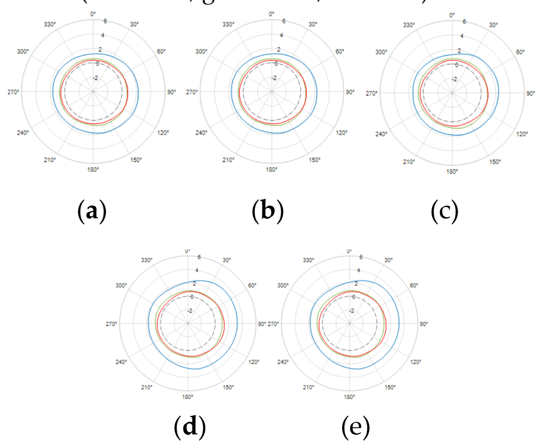

Figure 4. MTP-angle (α) plotted over the crank-cycle, positive: MTP-plantar- flexion (blue: DF1, green: DF2, red: DF3, dashed: zero). (**a**) I1; (**b**) I2; (**c**) I3; (**d**) I4; (**e**) I5.

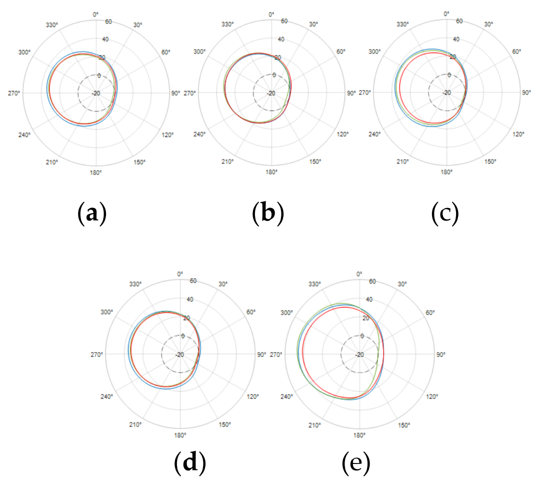

Figure 5. Pedal angle plotted over the crank-cycle. Negative values: heel down, positive: heel up (blue: DF1, green: DF2, red: DF3, dashed: zero). (**a**) I1; (**b**) I2; (**c**) I3; (**d**) I4; (**e**) I5.

The pedal-angle showed minimal differences for the four seated trials (I1...I4) only sprint data (I5) revealed different kinematics with more distinct heel-up (positive angle) than during seating for DF1...DF3. The minimum angles were close to zero for most trials and showed some heel-down (negative angle) in some cases, only DF2 had negative angles throughout all seated trials, all in Q1-Q2 (45°-225°) . For I5 a generally more pronounced heel-up posture could be seen, only for DF2 it was smaller (Figure 5).

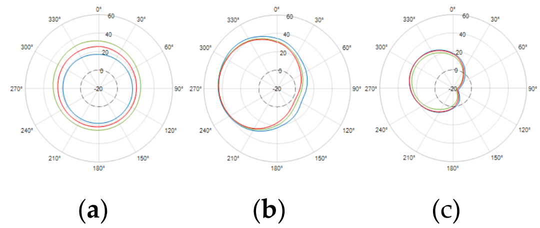

Figure 6. Pedal angle in I4 over the crank-cycle for three individual subjects. Negative values: heel down, positive: heel up (blue: DF1, green: DF2, red: DF3, dashed: zero). (**a**) constant heel up; (**b**) oscillating heel up; (**a**) oscillating heel up - down.

Although the mean data for the pedal-angle over all subjects showed no noticeable differences for the shoes, a closer inspection of individual patterns revealed that there were three different types of pedalling techniques which are shown in Figure 6.

Power output was evaluated and showed no significant influence of the shoes for the seated trials, which was expected as subjects were using a given gear ratio and cadence. Only for the sprint trial (I5) power value differences between subjects were more distinct (Table 1).

Table 1. Mean minimum (min) and mean maximum (max) power output in [W] for I1…I5 for all subjects (rounded to integers).

P[W]	I1	I2	I3	I4	I5
min	97	128	163	226	740
max	99	132	170	233	788

4. Discussion

It could be shown that there is a negative relation between sole stiffness and MTP-angle, where the difference between a nylon and a carbon insole were very small even for high power output. Pedal angle is not influenced by shoe stiffness but shows distinct individual differences between single subjects, which can - based on the given sample - be separated into three different groups: (a) constant plantarflexion, (b) oscillating plantarflexion, (c) oscillating dorsalextension-plantarflexion (cf. Figure 5).

5. Practical Applications.

Practical applications of the present research are conceivable for both leisure and competitive cycling and conclusions can be drawn for industry. Hybrid shoes - according to the data acquired - do not need to be extremely stiff to prevent excessive plantarflexion - DF2 and DF3 have quite similar results. For leisure cycling this would allow the construction of shoes for cycling and walking using comparatively cheap materials. As only plantarflexion was observed, shoes for dual use can be developed which can be adapted for walking allowing MTP-dorsiflexion while providing sufficient stiffness for power transmission. However, it should be considered that using an EVA material (DF1) resulted in excessive plantar flexion during cycling and might not be suitable for such a shoe.

Concerning competitive cycling, one practical application that might be of increased interest is in triathlon racing as it could be a step towards the evidence-based construction of a hybrid cycling-running shoe as already mentioned by Sterns, Hurt, Wilkinson, & Kram (2022).

Future research in this field should therefore focus to ascertain correlation of specific stiffnesses and foot biomechanics for both cycling and walking/running.

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Conflicts of Interest: Study design, interpretation of data and manuscript writing were done in collaboration with Vaude's R&D department (i-lab).

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