# EFFECT OF DIFFERENT PEDAL-SYSTEMS AND CADENCES ON PLANTAR PRESSURE DISTRIBUTION DURING PEDALING ON AN ERGOMETER AT CONSTANT POWER LOAD

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## 1 Abstract

*Every ambitious cyclist uses cycling shoes and special pedals to have a better connection to the bike during pedaling and aims an increasing energy transmission ratio. Recreational cyclists do not use those kind of pedals because it is unnecessary for their use.*

*This paper shows the effect on plantar pressure distribution between two very common pedals systems: the Shimano® SPD mountain bike system and the Look® KéO. As reference it is compared to standard platform pedals used with standard sneakers.*

*For a better comparison the power load of the stationary ergometer is constant and chosen shoes are from the same product class.*

*The hypotheses are that the pressure must be less when the cadence increases with every pedal/shoe combination.*
*Also the mountain and road bike pedals should provide a better energy transmission ratio.*

*All measurements were made with three different cadences – 60rpm, 80rpm and 100rpm which represent the main used cadences when cycling outdoor.*

*Because of the used measuring system only one foot could be observed with is important for interpretation of the results.*

## 2 Introduction

Although general bicycle design has not been changing for centuries, new performance records are continually being achieved in professional cycling. These results are partly credited to improvements in bicycle technology even if they provide only small advantages in many cases. Due to the fact that cycling is a quite multifaceted kind of sport affected by many different types of parameters opinions of experts are varying about the importance of those factors and their influence ability. One of these often discussed issues is the existence of the so called "smooth pedaling stroke". The pedaling cycle (360 degrees) can be divided into four sectors (ref. to Figure 1), where each of these sectors include a certain rotation segment, according to the remarks of Henke (Henke, Monfeld, & Heck, 2001).

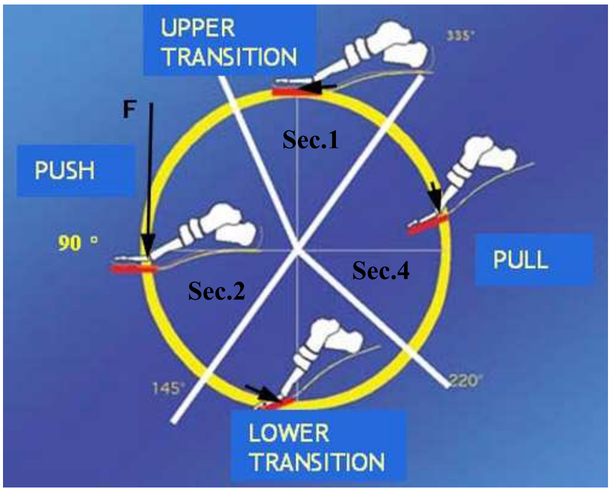


Figure 1: Schematic design of the pedaling cycle including amount and orientation of propulsion-effective forces (source: http://thebloomingpoint.com/ revelox-innovative-bicycle-crankset-version-rc1, May, 30th)

By considering biomechanical relationships the force attached by the rider can be distinguished into an effective (for propulsion) proportion acting perpendicular to the crank arms (or tangential to the chain ring) also called the tangential force (TF) and an ineffective amount acting in-line of the crank arms direction or radial to the crank axis and therefor called radial force (RF). While the knee (M. quadriceps) and hip extensors (M. gluteus), which are mainly contributing to the pedal stroke, develop their greatest amount of force in the second sector, thus TF reaches its maximum during this phase also (at a crank position of 70 to 90 degrees), irrespective of the rider and his riding abilities (ref. to Figure 2 (A)). TF decreases until it is nearly zero in 180° position of the crank. Due to the body mass creating a force vector orientated vertically also the force attached by the rider to the pedal is in-line with the crank arm direction and therefor the propulsion-effective proportion of the pedal force is zero. Using a clip less pedal system one could create a TF amount by pulling the pedal backwards (posterior) in horizontal direction, which would afford hamstring activity for knee flexion but also an active pedal discharge in vertical direction (ref. to Figure 2 (B)). However not many cyclists, neither professional nor recreational ones use this technique in practice. During the following fourth sector, the so called regeneration phase because of the absence of any propulsion-effective pedal force proportion, the body weight can indeed create a negative counter-productive force amount. It had been documented by several authors that some professional cyclists are able to limit this negative force amount by an active vertical pull movement during the third sector although there are not many cyclists practicing this technique and it had not been prospected to turn the force vector to positive sign in sum (creating additional propulsion effective force). In the first sector, characterized by the area around the upper transition the conditions are quite similar to sector three due to the vertical upright orientation of the crank arm. The only ways to generate TF in this position are by tilting the pedal out of the horizontal position by extending the ankle joint and thus splitting the pedal force into a tangential and radial proportion or by using clipless pedals and actively pushing the pedal forward (anterior) horizontally.

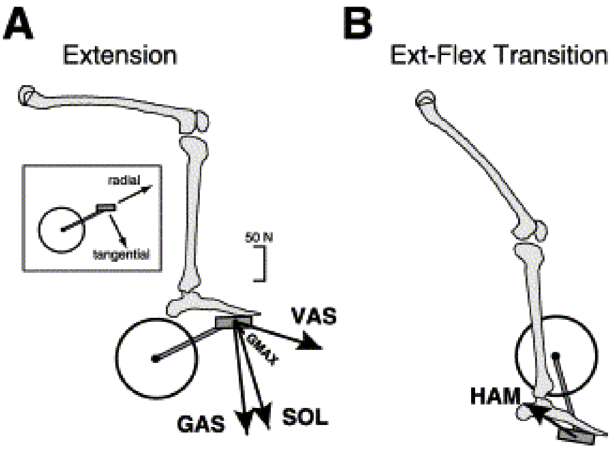


Figure 2: crank positions at (A) point of maximum TF and (B) lower transition and involved muscle activity (source: http://www.gaitposture.com/article/S0966-6362%2802%2900068-1/abstract, May, 30th)

The theoretical "smooth pedaling stroke" is based on the principle of minimizing the ineffective proportions of the pedal force to virtually zero, which is not possible due to biomechanical conditions of the system bicycle ← → rider, while maximizing the effective proportion at once (Emanuele & Denoth, 2008). Furthermore these principles described have to happen at constant crank torque and continuous pedal rate. Actively charging and discharging the pedal load in the appropriate position and an adapted pedal orientation in every crank position, affording a high amount of ankle joint flexibility, had been proved to suit these requirements most effectively (Uhrbach, 2010).

One of the most determining parameters for pedaling technique mentioned before is cadence. The rider`s individually chosen cadence in relation to the given terrain conditions is a significant criterion to separate professional cyclists from hobby cyclists or recreational ones. The resulting pedaling performance corresponds with the product of pedal force and pedaling rate. Depending on the given case there are two possible approaches which can be applied. The one practicable for professional cyclists under race conditions is maximization of power output at maximum possible effort (Redfield & Hull, 1986), (Watson & Swensen, 2006). For this study authors prefer the approach of highest economy (minimization) of effort for a given power objective (Bachl, 1985).

In order to force slow and enduring muscle fibers, so called slow twitch fibers (ST), to work at a given pedaling performance, professional and advanced hobby cyclists choose higher pedaling cadences which result in lower required pedal forces. Lower cadences as preferred by recreational and average hobby cyclists provide the advantage of less affordable intramuscular coordination but force more activity of fast twitch fibers which provide the ability to deal with higher forces but tend to fatigue faster. This kind of pedaling technique is not useful for long enduring races and is only applied by professionals for fast acceleration or sprint distances. Like every motor the human body provides highest economy of approach at a special rate of activity, determined by the cadence in cycling. Several authors concluded that highest muscular economy for human pedaling motion is settled at 60 to 90 rpm (Bachl, 1985), (Emanuele & Denoth, 2008). In real the majority of professional cyclists choose much higher cadences than those expected to be most economic (110 to 120 rpm). Löllgen stated that this effect appears due to non-linear power perception of cyclists (Löllgen et al, 1980). The higher cadences seem to be more comfortable to them in order to overcome high loads. Another aspect regarding professional cyclists is that they are not competitive at low cadences leading to a lack of flexibility to altering environmental conditions during race. Choosing the appropriate cadence during race and training in order to adapt to changing conditions and situations is one of the hardest quests for professional cyclists to cope with. In addition the freely chosen cadence can indicate a rider`s comfort or discomfort resulting from inappropriate adjustments or even the wrong saddle or frame size.

From the rider`s view of sight there are two interfaces between the muscular power he produces and the propulsion he can create via the drivetrain. One of these interfaces is the foot-(shoe-) pedal interface converting the muscular force to rotary mechanical force over the chain which is a major topic of this study. Modern clip less pedals, like they are used (with some small technical improvements) in professional cycling sport for centuries, provide two fundamental advantages. On the one hand the energy-losses caused by conventional platform pedals and casual footwear due to slipping, material deformation and a lacking mechanical connection are limited and on the other the regeneration phase (fourth sector) of the pedal stroke can be used for generating additional propulsion due to a fixation of pedal and shoe. Actual cycling shoe models offered with highly-stiff carbon outsoles enforce the advantages of system pedals leading to a highly efficient shoe-pedal combination with the aim to minimize energy losses. Although there are several different system pedal types on the market not many comparing studies were published. The most common pedal system concerning road race bicycles is the one from Look® (Look Cycle International, NEVERS, France). Because of its large-area connection cleat improved energy transmission features and a smoother distribution over the ball / midfoot region were postulated by the manufacturer. In professional mountain biking sports (MTB) the Shimano® SPD-standard is widespread, probably rooted in a higher adjustable freedom of movement of lateral and medial lower limb rotation. From the view of biomechanical efficiency it is propagated among experts that force transmission ratio of the Look-system is higher than those of SPD-standard although no documented proof justifies this claim. A comparison of these systems at different cadences will be part of this study to discuss whether this allegation can be verified or not.

One aim of this investigation was to clarify the connections between cadence and applied pedal forces (or in this case pedal pressure distribution) for a given power load condition. It had to be determined how the plantar force distribution measured via an insole pressure measurement system responds to differing cadences. Due to the connections between cadence and applied pedal force under constant power load conditions mentioned before it is assumed that the configurations with the highest cadence (100 rpm) will provide the lowest pressure values, i.e. configuration SPD/100 will provide a lower absolute pressure value than SPD/80 while this value will be lower than the one of SPD/60. This behavior must be observed over all pedal/cadence combinations for verification of this hypothesis. The second aim deals with the relationship between advanced cycling pedal/shoe-systems and its effect on plantar pressure distribution compared to conventional platform pedals. As already mentioned before system pedal / cycling shoe combinations are claimed to provide highly improved energy transmission ratio, which is assumed to be visible in shape of lower cadence/pressure product values for a given power load condition compared to a conventional platform pedal shoe combination.

## 3 Methods

One physically healthy male student (S1) took part in this investigation. S1 was 22 years old, 178 cm tall, had a weight of 68 kg and a BMI of 21.46. He was right foot dominated and active triathlete performing on professional level. Furthermore S1 is free of any lower-extremity disorders.

The measurement test routine included three sets of pedaling exercises to perform for each of the nine given pedal/cadence configurations (ref. to Table 1). The used ergometer was equipped with an integrated eddy current brake to maintain a continuous load and a two-sided pedal providing a platform on one side, which was chosen for the first configuration setup, and a clip less SPD system on the other. For condition one S1 was wearing his casual footwear. The second configuration involved a combination of Shimano MTB cycling-shoes of type SH-M225 providing a CFK-reinforced outsole and a Shimano SPD-standard pedal of type M980. For the third configuration Shimano road cycling-shoes of type TR70, also equipped with CFK-reinforced outsole, were used in combination with a Look-pedal of type KéO Classic. For each configuration sets were done at a power load of 200 W and at cadence steps of 60, 80 and 100 rpm. All single cycling sets were executed with a recovery time of one minute in between. S1 was asked to carry out the cycling motion in a natural way of his own discretion under the given conditions. The constant load was adjusted according to the setting and monitoring display of the ergometer. To keep the cycling motion at the respective cadence the displayed cadence value was monitored by S1. In order to maintain constant pedaling fluency during measurement run, a run-in phase of about 30 seconds until cadence could be kept easily by S1 was performed in advance of every measurement run.

Table 1: setup configurations for measurement routine

| pedal type | cadence [rpm] | | |
|---|---|---|---|
| | 60 | 80 | 100 |
| platform | 3 sets | 3 sets | 3 sets |
| road (Look®) | 3 sets | 3 sets | 3 sets |
| MTB (SPD®) | 3 sets | 3 sets | 3 sets |

The measurement of the plantar pressure distribution was performed by using the insole pressure measurement system MediLogic© (T&T medilogic Medizintechnik GmbH, Schönefeld, Germany). The MediLogic system, consisting of two insoles (in various standardized sizes) for left and right, a transmitter and a receiver plus evaluation software provides in-shoe measurement of pressure distribution over a wireless data transfer interface. Depending on the size of insoles, each insole is equipped with up to 240 integrated force sensors, which are distributed in matrix pattern over the whole insole surface. In advantage to common FSR-sensors the MediLogic sensors are value calibrated and thus provide a quantitative evaluation of pressure values. Each single sensor has a measurement range from 0.6 to 64 N/cm². The used insole size in this case was 42-43 and pressure measurement records were taken only from the right hand side. The single distributed sensors of the sole were grouped to patterns matching anatomical plantar regions. Overall the sensor matrix was divided into six plantar regions including the hallux (HA), the medial (MF), central (CF) and lateral forefoot (LF), the medial (MM) and lateral midfoot (LM) and the heel (H), where especially HA, MF, CF and LF were of certain interest for this study (ref. to Figure 3). For each region a mean value consisting of the involved single sensors was calculated to represent the current pressure distribution value of the respective region.

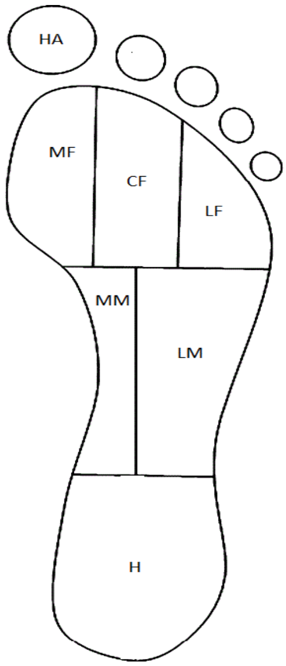


Figure 3: Anatomical plantar scheme for clustering of Medilogic-sensors into the six regions hallux (HA), medial (MF) / central (CF) / lateral (LF) forefoot, medial (MM) and lateral midfoot (LM) and heel (H) (source: http://jbjs.org/article.aspx?Volume=82&page=939, May, 30th)

Sampling rate was set to the maximum available value (300Hz) providing 180 samples for one consecutive crank turn at the highest occurring cadence (100 rpm). For each shoe configuration a separate calibration measurement run, with completely load discharged insoles, had been recorded for consideration of value offsets for further measurements. To get information about every completed consecutive crank turn a contac-free solenoid switch was installed at the side of the ergometer body in 0° crank position in the area behind the rotating crank arm. The associated solenoid was mounted on the crank arm facing the solenoid switch whenever it reached 0° crank position. The solenoid switch generating a trigger signal after every consecutive crank turn acted as a digital input signal to the Medilogic system by using the additional Medilogic I/O-interface box. After the initial run-in phase every measuring cycle record was taken for 15 seconds. The first two crank turns of each measurement run were ignored and the following five turns were used for the representative mean value of this cycle plus calculation of standard deviation. Considering the three runs for each configuration, this results in one consecutive mean crank turn, out of 15 single crank turns for each of the nine configurations. The whole recorded raw data including the trigger signal were exported for further processing. All necessary computations were performed in MatLab (V7.11.0 (R2010b), The Mathworks Inc., Natick, MA, USA). To establish the connection between crank position and the recorded samples, every sample series representing a full pedal turn was interpolated to 360 values representing one value for each degree of crank rotation. After data processing six by nine mean value and standard deviation vectors, one for each pedal/ cadence configuration multiplied by the six plantar regions, with a resolution of one value per degree were gathered. In addition the maximum value of the sum of all regional pressure values over the whole crank resolution was evaluated for every of the nine configurations. These maximum values were compared to each other in order to get a conclusion to question 1. By multiplying these values with the related cadence a pedaling power corresponding value results which can be used for answering question 2.

## 4 Results

To visualize the results, figures of every analyzed area are mentioned. Every figure contains three graphs for every analyzed cadence (60, 80 and 100rpm). The progression of the mean pressure of an area shows an average cycle of the measured pedaling cycles.

Figure 4 shows the progression of pressure in the HA area with a platform pedal, figure 5 and 6 the same with a road pedal respectively a SPD pedal.

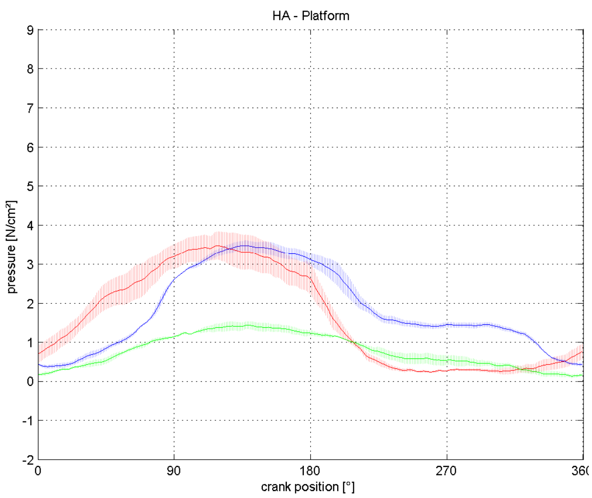


Figure 4: progression of mean pressure of HA during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

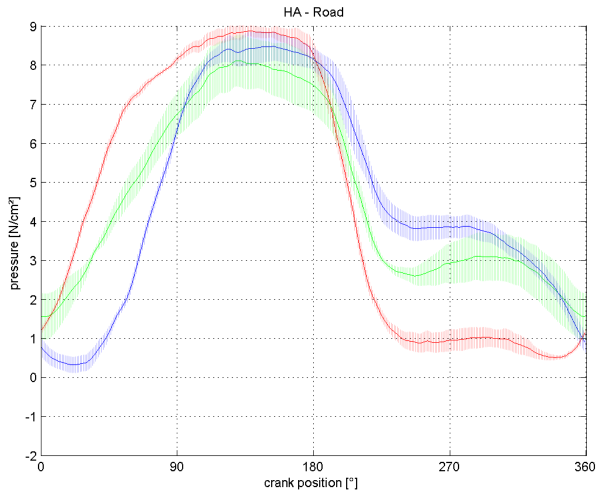


Figure 5: progression of mean pressure of HA during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

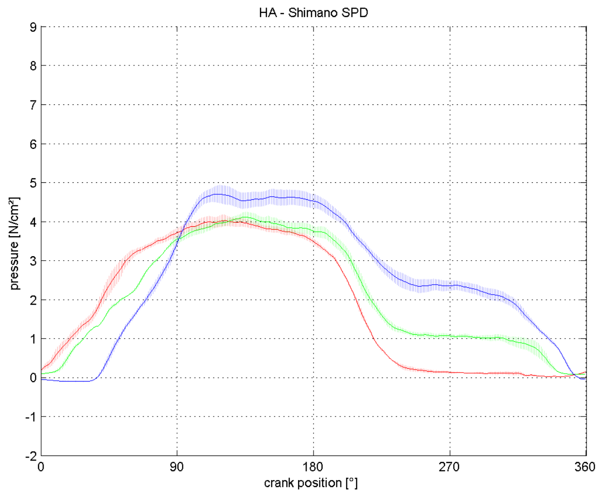


Figure 6: progression of mean pressure of HA during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

Conspicuous is that the pressure in the HA area is about 40% respectively 50% higher than with a SPD pedal or platform pedal. No matter which cadence analyzed.

Figure 7 shows the progression of pressure in the MF area with a platform pedal, figure 8 and 9 the same with a road pedal respectively a SPD pedal.

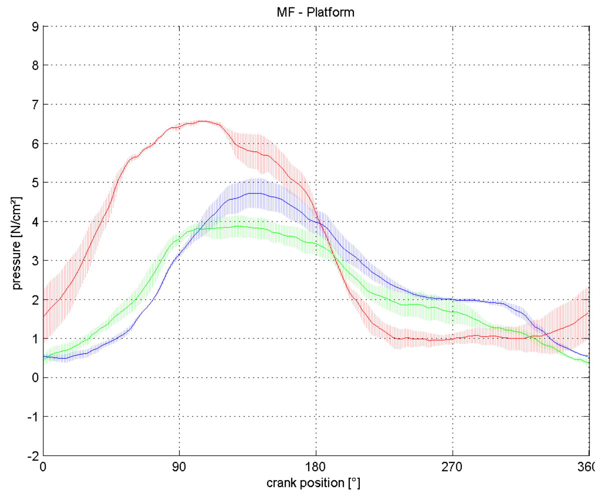


Figure 7: progression of mean pressure of MF during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

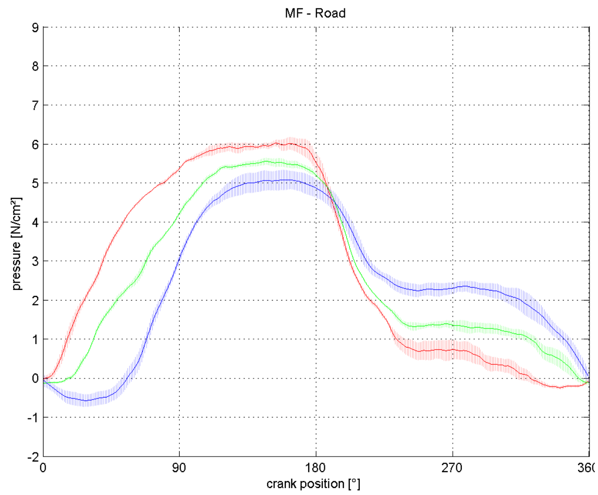


Figure 8: progression of mean pressure of MF during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

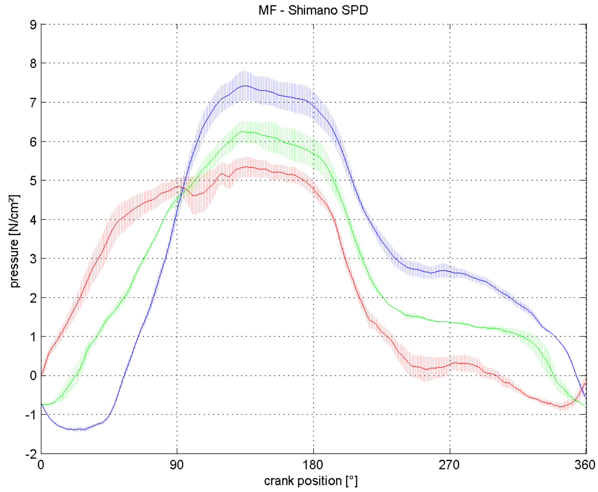


Figure 9: progression of mean pressure of MF during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

The graph characteristics of road pedal and platform pedal are similar. But with 60rpm on the platform pedal the pressure peak comes at 90° crank angle, compared to this peaks normally appear at 120°-135°. Noticeable is also that the highest pressure with a SPD pedal is measured with 80rpm.

Figure 10 shows the progression of pressure in the CF area with a platform pedal, figure 11 and 12 the same with a road pedal respectively a SPD pedal.

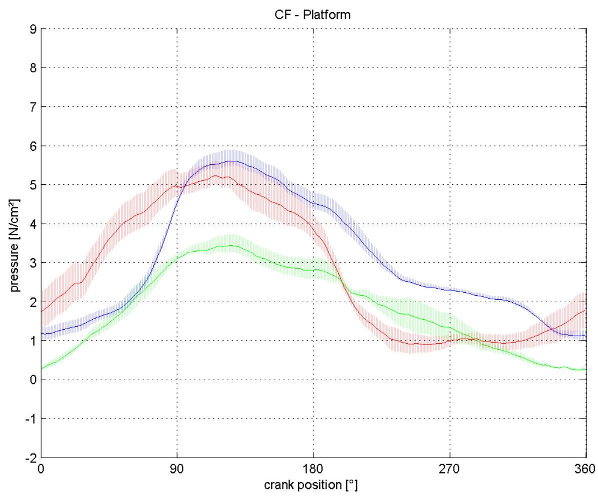


Figure 10: progression of mean pressure of CF during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

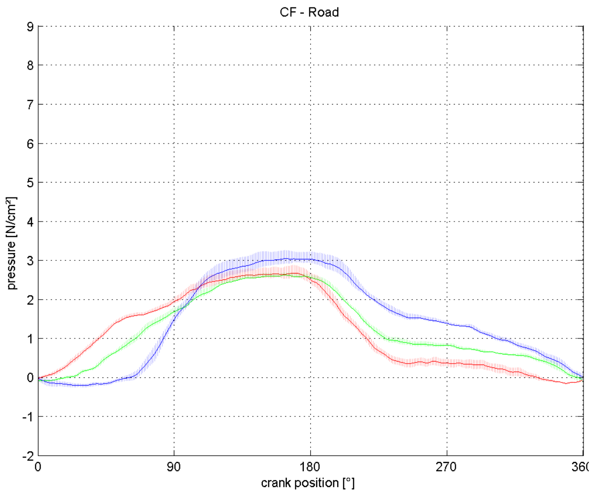


Figure 11: progression of mean pressure of CF during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

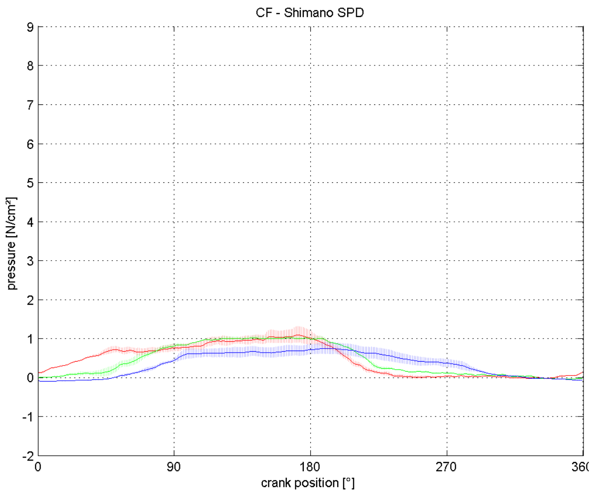


Figure 12: progression of mean pressure of CF during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

The progression of pressure is almost not noticeable with SPD pedals in the CF area. The graphs of road pedals and platform pedals compared show a 30%-40% higher pressure with platform pedals in this area. Except with 100rpm, than the characteristic of the progression and its values are similar.

The analyzed areas LF, MM, LM and H do not show meaningful progressions of pressure and cannot be used to verify the mentioned hypothesis. For example figure 13 shows the progression of pressure in the H area with a platform pedal, figure 14 and 15 the same with a road pedal respectively a SPD pedal.

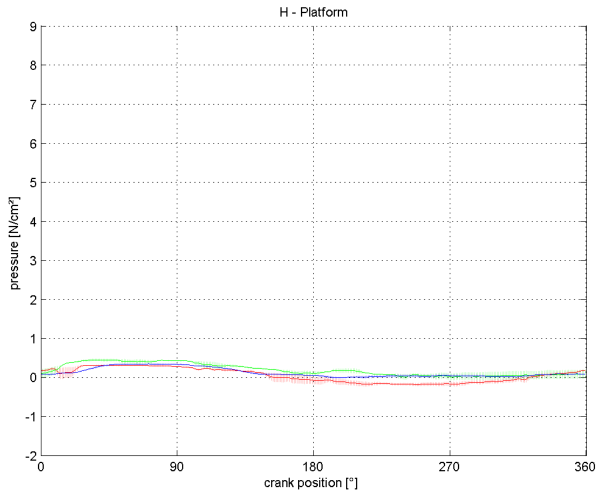


Figure 13: progression of mean pressure of H during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

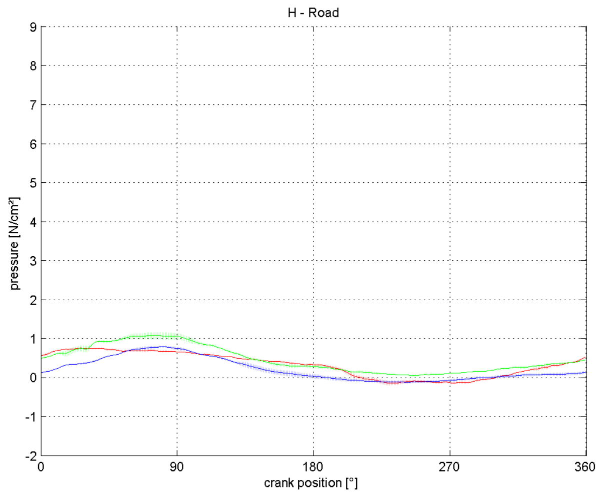


Figure 14: progression of mean pressure of H during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

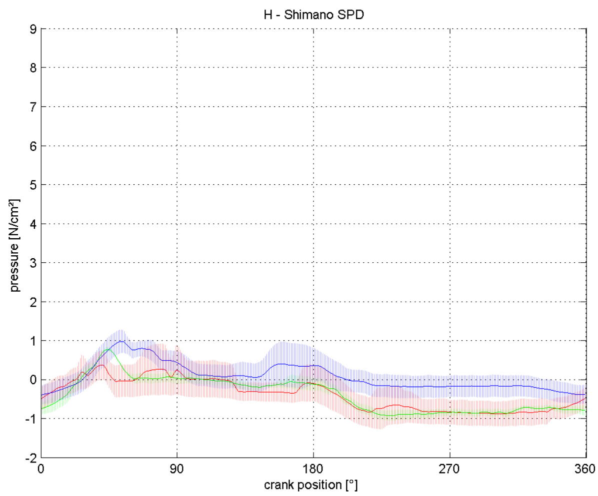


Figure 15: progression of mean pressure of H during an average cycle; red - 60rpm, blue – 80rpm, green – 100rpm

No graph shows any significant progression. No matter which cadence or pedal system is chosen.

## 5 Discussion

The first hypothesis could not be verified with the used measuring system. With platform pedals the set hypothesis that the pressure must be higher when the cadence decreases is right. To verify the hypothesis with chosen advanced pedal systems both plantar pressure distributions (left and right) have to be analyzed. That's because a pull phase during a pedal cycle was observed indicated through negative pressure values. That means the ratio between pull and press phase during pedaling is not defined.

The second hypothesis that SPD and road bike pedal / cycling shoe combinations are claimed for improved energy transmission ratio compared to a conventional platform pedal shoe combination, could not be verified either. The difference of the energy transmission ratio is too low to be measured with our measuring system. However, an interesting point of the measurement is that the pressure distribution is noticeable different with every pedal / shoe combination. With platform pedals the distribution is as expected, almost all pressure under the forefoot, less under the big toe and no important pressure under middle foot and heel. The road pedal/shoe combination produces a much higher pressure on the big toe and the SPD pedal/shoe combination on the medial forefoot.

However it hast to be said that shoe geometry is very important for plantar pressure distribution. All measured data is based on used shoe models.

The conclusion is that for those set hypothesis an analysis of left and right feet is necessary. But it is shown that a pedal/shoe combination changes the pressure distribution dramatically.

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