The Need for Data-driven Bike Fitting: Data Study of Subjective Expert Fitting

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Abstract: The number of cyclists is growing rapidly, for commuting but also as a sport. With this growth, there has been an increasing interest in cycling position. Trainers, athletes and bike vendors acknowledged this and started to perform bike fits. As these experts have different backgrounds and varying levels of expertise, it was hypothesised that this could have an influence on the outcome in terms of the advised position. In this research three cyclists were bike fitted by nine different bike fitting studios. It was hypothesised that, as different bike fitters use varying techniques and have different experience levels, the cyclist would be advised a different optimal position by these different bike fitters. The preconceived hypothesis was confirmed as the range of advised positions in both saddle height and setback was up to 3 cm. Data-driven bike fitting can help bring down these considerable differences amongst fitters and will be discussed in the last chapter.

1 INTRODUCTION

Bike positioning has always been a controversial topic, ever since riders could adjust their saddle height, there has been a debate on the "optimal" cycling position. Eddy Merckx, one of the greatest cyclists of all times, sometimes even changed saddle height within races. Also, as more and more people started competitive and performance-oriented cycling, research in the domain of cycling biomechanics has been on the rise the last decade. Yet there has been little research regarding cycling position. There are a lot of theories on bike positioning and bikefitting, which is the process of making adjustments to the bike until the optimal position for a certain individual is reached. However, the scientific evidence behind these fitting theories is lacking to date.

Historically, bikefitting has generally been the end result of following some general rules of thumb. Later on tools such as a plumb line and goniometers became available and bikefitters, which usually mastered the "art of bike fitting" by lots of exercise and perseverance, were now also able to make some static measurements. Nowadays, as technology made a huge leap forward, some great aids like motion or video analysis found their way in the bikefitting process (Burt, 2014).

In the motion analysis segment of the market, two major players exist, being Bioracer Motion (Tessenderlo, Belgium) and Retül (Boulder, Colorado, USA). They both use active markers, which are attached to the body to provide realtime and high-resolution measurements of body angles and position during the actual cycling motion. Video analysis software tries to achieve the same purpose by measuring certain angles based on video footage in which the user is requested to mark the reference points for motion tracking manually. Evidently, this manual segment identification is less sensitive and specific for precise kinematic analysis purposes compared to a marker-based motion tracking system

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which allows three-dimensional real-time motion tracking without user intervention. These technologically more advanced techniques, are ultimately providing more insight in the actual cycling biomechanics and might reveal discrete imbalances or positioning errors, invisible to the naked eye or absent in static evaluation conditions. More so, they also often prove to be more accurate. Especially due to the fact that statically measured angles may differ from those that are measured dynamically (Garcia-Lopez & Abal del Blanco, 2017). Thus, it is a fact that modern bikefitters have a greater range of technology at their disposal compared to their predecessors in the past. Unfortunately, having modern technology does not always lead to benefits for the client. Education remains important, buying the most advanced system will not necessarily make you the best bikefitter.

A competent bikefitter will pay attention to its customer and his/her personal goals. Principally, a bikefit is a compromise between comfort, performance and injury-prevention. A professional rider will pay a lot of attention to his performance level, because his goal is to ride as fast as possible and beat the opponents. On the contrary, a rider that just rides a sunday spin with the local cycling club wants to do this as comfortable as possible. However, these two ridertypes have usually one thing in common; they both do not want to get injured. To achieve their respective goals, they each need to be placed in an individualised optimal cycling position. Nonetheless, when participating in a mass cycling event and taking a glance at colleague riders, an awful lot of cyclist could be observed which are not riding in their optimal position. Consequently; a lot of complaints about saddle discomforts and painful knees or lower backs exist within the cycling community, possibly due to insuffucient bike fit (Alta, et al., 2014). A lot of experts in biomechanics, sports science or kinesiology recognized this gap in the market, and are fitting people to their bikes. With the large choice of bikefitting technologies and the different backgrounds of the actual fitters in mind, the inevitable question arises: “Does bikefitting suffer from some kind of subjectivity?”. In other words does a client always get the best position for his/her needs; and does the fitter’s background or his methodological approach affect the vision on the “optimal position”.

2 METHODS

Bike Fitting Procedures and Data Collection: In general, the bike fitting process can be divided in two parts. A first stage of the fitting process is mainly focused on the lower body, mainly altering seat height, saddle setback and adjusting the rider’s cleat position. The next stage is the upper body posture, which is determined by handlebar reach (stem length and the fixed saddle setback) and the handlebar drop (number of spacers and the degree of the stem).

For the lower body, two general rules exist in bike fitting. These are respectively the safe knee angle range and the Knee Over Pedal Spindle (KOPS) technique. KOPS is defined as the distance that the patella comes over the center of the pedal spindle when the pedal is at the 6 o’clock position. Correct adoption of these two basics should ideally result in tight ranges across the different bike fits.

For this research, three different cyclists with differing performance levels and training ambitions were sent to nine different bike fitting studios. All of them giving their consent to participate in the experiments and to publish the results. One of them was a highly competitive rider, another one a long distance rider and the last one concerned an older but still very active cyclist. This undeniably has an influence in terms of the opposed limitation for each test person, a highly competitive rider will most likely be a lot more flexible which allows for a more aerodynamic setup. Each of the consulted bike fitting studios adopted another methodological bike fitting approach, using their prefered technology based on a particular bike fitting vision. To analyse the intra and inter system variability, the studios where chosen in function of their fitting technology. Three studios used the Bioracer Motion system, three others used the Retül system and the last three used other miscellaneous techniques; i.e. video, saddle pressure, etc. The consulted bikefitters were located in Flanders, Belgium. The three participating riders were asked to take personal notes immediately after each bikefit to give an idea of how the test person had actually experienced the bikefit. Particularly, comments regarding customer-friendliness, the duration and fluency of the fitting procedure as well as the participant’s subjective perception of comfort and content with the resulting cycling position were registered. In addition to that, our test persons asked on which parameters the fitter based his decision to do adjustments. Furthermore, all bikefitters gave the test subjects a report including the detailed measurements of their endfit. These collected data ultimately made an in-depth comparison of the different bike fitting studios possible.

Each of the fitters could ask for the same amount of information, the participants were in no way restricted to answer any of the fitter's questions. To have zero bias in the bike fitting procedures, every rider started each bikefit with the same configuration (bike, saddle, crank length, saddle height, setback, reach, handlebar width). After each bikefit, the bike was adjusted back to the starting position. If the bike fitter advised insoles or wedges to improve the cycling movement, these were also removed after the bikefit as these can also have an influence on cycling biomechanics (Yeo & Bonanno, 2014) . All these precautions were taken to ensure that each bike fitter started off with the same baseline. To analyze subjectivity, the reports (Figure 1) of all the end fits of each of the bikefit were collected.

Figure 1: Position before and after the fitting, subject has a straighter pelvis and smaller knee flexion after fitting.

The fitters relying on motion or video analysis often provided a quite detailed report (Figure 2).

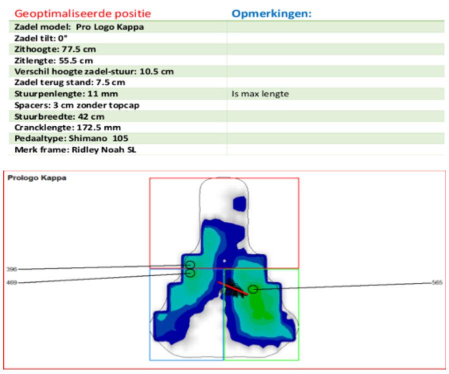

Figure 2: Extract from a fit report (including saddle pressure analysis, original fitting instructions - in Dutch).

Other fitters, rather relying on static measurements and their experience, were generally providing their measurements on a single sheet of paper.

In order to compare the different methodologies, the following measurements were extracted from the fit report: saddle setback, saddle height, handlebar reach, handlebar drop and fitted stem length. Advices which weren't actually tested during the fit were ignored during this process.

After the various bike fits, each of the end positions was thoroughly assessed. This assessment consisted of the evaluation of the rider's symmetry and stability on his bike, as well as his motion quality via motion analysis. For the evaluation of symmetry and stability, the Bioracer Motion software (Dierckx, 2019) was used because it is the only tool that allows for simultaneous bilateral analysis.

Data Analysis:

The fitting data collected in the fitting reports as well as data on rider's symmetry, stability and cycling motion were analyzed in three ways.

Firstly, a comparison between the recreational rider and the pro rider was made (Table 1), examining if there were consistent differences in drop, back and shoulder angle and lower body movement. It was hypothesized that a pro rider would be bike fitted in a more aerodynamic position. Mainly because his goal is to be in the fastest, yet sustainable, position as possible, but also due to the large training loads, this type of rider became a lot more flexible and accustomed to the cycling position.

Table 1: Subject characteristics.

#	Age	Height	Inseam	Cycling experience	Type of cyclist	Disciplines	Bike	Frame Size	Frame Stack	Frame Reach	Head tube	Flexibility	Pedal system
1	25	176.5	83.4	10+	competitive, elite	Road, CX, MTB	Wilier GTR	M	55.6	38.7	15.1	Very flexible	Speedplay
2	24	177	87.1	2	recreational, long distance	Road	Ridley Noah SL	S	54.2	38.4	14.5	Normal	SPD-SL

Secondly, the differences in bike fitting characteristics in between fitting studios were examined. It could be interesting if one studio is, for example, striving for other knee angles or has a completely different approach towards bike fitting.

Lastly, the different fits were compared to one another for each of the participants. The goal of this last examination was to provide an insight in how large the differences are between the different end fits, first in terms of position measurements, but then also in regard of the direct biomechanical consequences of this position, as measured by motion analysis (i.e. knee angles, KOPS, etc.).

3 RESULTS

The results are presented in two parts. Firstly, the analysis of the end fits, where only the position of the bike is considered, is presented. Secondly, the results regarding cycling position, resulting from the different fitting procedures, based on assessment of symmetry, stability and motion in our lab after the bike fits is demonstrated.

It is remarkable that one of our test persons had to cancel his last bike fits due to knee inflammation. It is not known if this was due to the different cycling positions that were tested by the bike fitter. However, this certainly might be a possible cause as our other recreational rider also had similar issues after the same series of bike fits. This only indicates that a suboptimal cycling position might put extra stress on the body, ultimately even causing injuries. Normally it would be stated that a bikefit can be beneficial and reduces the stress on the joints. From this research, in contrast, we evidently have to conclude that a bikefit proves to be a valuable tool to prevent injuries only if it is performed properly by an expert.

3.1 Analysis of End Fits

The results of the executed investigation, as already briefly mentioned, confirmed that different bike fitters indeed advised a different “optimal” position. Surprisingly, the differences in end-fit characteristics between the different fitting approaches were situated in a centimeter - rather than millimeter range, as originally expected. Figures 3, 4, 5 and 6 respectively show the ranges of saddle setback, saddle height, handlebar reach, and handlebar drop for 2 out of the in total 3 participating test persons (Table 1).

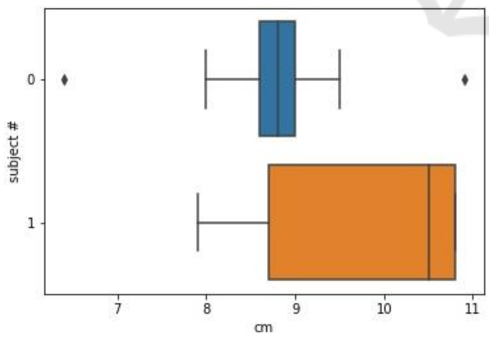

Figure 3: Handlebar drop for 2 subjects compared.

Another thing that was quite alarming and which can easily be observed in the seat height boxplots (Figure 5) was that for the participant with a 4 cm larger inseam, one bike fitter suggested a seat height which fell in the exact same range of the other participant with a significantly smaller inseam.

Unfortunately, the lower body rules, discussed in the methods section, were clearly not used by every fitter, which led to higher ranges, as can be seen in the scatter plot in figure (Figures 7,8 and 9).

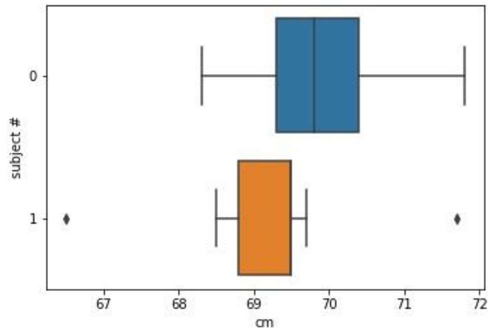

Figure 4: Handlebar reach for 2 subjects compared.

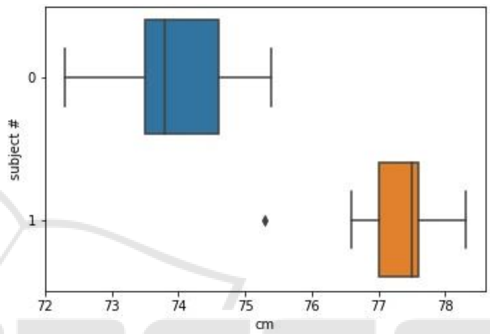

Figure 5: Seat height for 2 subjects compared.

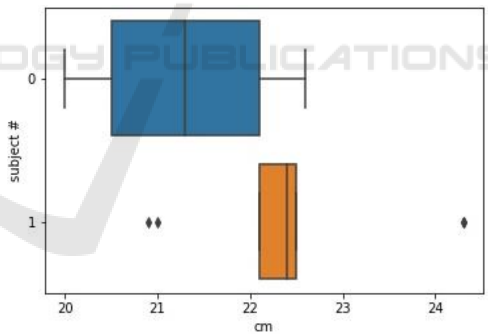

Figure 6: Saddle setback for 2 subjects compared.

Seat height was converted to the inseam/seat height ratio allowing comparison between different subjects. The colours of the dots represent the used fitting method. It is remarkable that Retül-assisted bike fits have the broadest ranges. Additionally, some fitters even left the initial bike setup unchanged even if the calculated angles weren’t within the safe ranges. They deemed that people with lots of hours in the saddle have a good feeling of which positions suits them best.

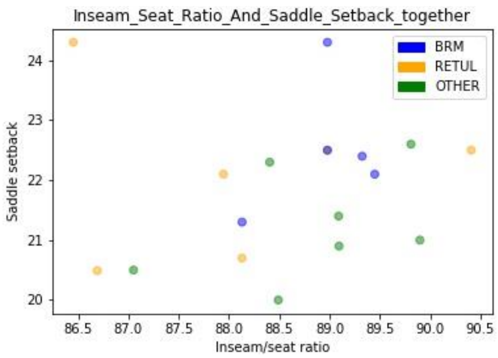

Figure 7: Scatter plot of inseam/seat height ration and saddle setback.

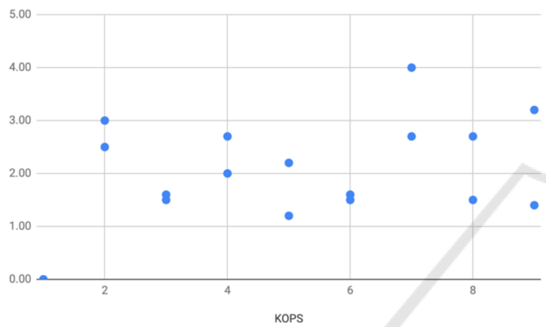

Figure 8: Scatter plot for different bike fitting studios in terms of KOPS.

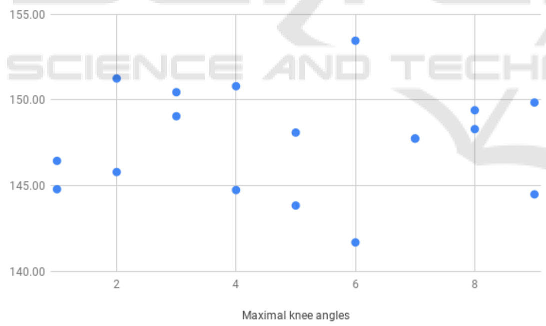

Figure 9: Scatter plot for different bike fitting studios in terms of maximal knee angles.

The recreational rider, who could maybe benefit from a more relaxed position, was mostly left in a somewhat aggressive position. However, this can be due to the limitations that are posed by the frame, as this rider was on an aero road bike. Fit bikes can solve this problem as you can try any possible position. The competitive rider was lowered down by most of the fitters but there wasn’t a general consensus on how low the handlebars should be dropped. In the end, saddle to handlebar drop became similar for both participants, which is very remarkable as they clearly differed in terms of training ambitions and overall joint mobility and muscle flexibility. It is also notable that, for the recreational rider, the Retül-driven bike fits suggested handlebar reaches and drops that were closer together than those for the competitive rider (Figures 4 and 5).

Lastly, the inter and intra system variances were analysed. This might give some interesting insights in what is needed for a more objective bike fitting methodology. If the inter system variance is very small for one system and larger for another system, it might be that the system is better suited for bike fitting or is easier to use. If the differences between fitters who use the same system are large, it might be an indication that those fitters need additional training with the system or require additional general bike fitting education. It is worth noting that more and reliable data will be necessary to fully confirm this hypothesis, but initial results of this experiment definitely show that additional investigation is needed within the bike fitting community.

As previously mentioned, there are often large differences in saddle setback between the individual fitters. However, our data shows that fitters using the Bioracer Motion system consistently seem to rely on the software to determine the ideal saddle height, which was within a range of ± 0.5cm for both test persons. This in contrast with fitters using Retül or other systems, where the observed variance was much larger (Figure 10). Further analysis of this inseam/seat height ratio was also performed.

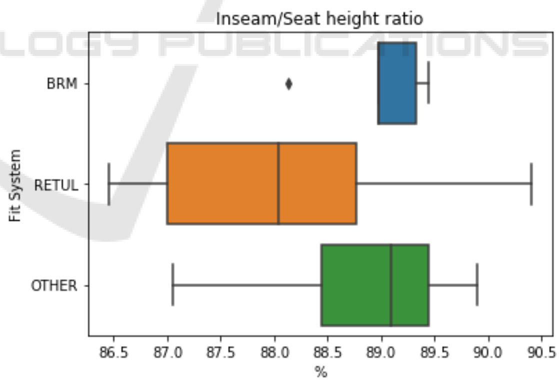

Figure 10: Boxplot of intra system inseam seat height ratio differences.

The results show that the Bioracer Motion (BRM) measurements were actually in a tight range (apart from 1 outlier). The end-results of the Retül fits were varying significantly more than the others. This somewhat large range might have multiple reasons. A first indirect reason could be that education of the people executing Retül bike fits could be further improved. Better experience and knowledge of the system will certainly improve the overall quality of the bike fits, independent of the adopted technology. Another possible cause is the system's suggested safe ranges for knee angles, which influence seat height, are too broad and should ideally be narrowed down. Retül systems suggest knee angles between 35 and 40 degrees (Burt, 2014).

A final interesting finding concerning analysis of end fits was that the rule of thumb of the saddle height, constructed by Greg LeMond (Burke, 2003), is actually very close to the average seat height between the different measurements. This formula states that the ideal saddle height is 0.883 times the inseam length, minus 3mm if the cyclist is using clipless pedals. This number is within a millimeter from the average of all end fits for both test persons. Which, once again, states that the rules of thumb from the past still have a certain value within the modern bike fitting procedure.

3.2 Motion Analysis

3.2.1 Comparison between Test Persons

Because test person X is a competitive rider, whilst test person Y is a recreational rider, it is expected that X will be advised to have a greater drop and reach to be in a more aerodynamic position. Flexibility is no issue for rider X, so little limits are imposed on the configuration of the bike. In contrast, rider Y has limited flexibility which might for instance have an influence on the maximal drop.

In contradiction to these assumptions, the recreational rider was advised a 9.77 cm drop (on average) as opposed to the pro rider with an average drop of 8.56 cm (Table 2). However, the handlebar reach of rider X is on average 1 cm longer than rider Y. To get a better idea of the influence on the riders' positions, these configurations were compared to one another with the Bioracer Motion system. From this data, we can conclude that the back angle is, on average, significantly lower for rider Y than rider X, and the pelvic tilt higher (Figure 11). This means that rider Y is riding in a more aerodynamic position as he is lowering his back when cycling. This large difference in back angle (32.89° in comparison to 38.62°), is very notable, especially as rider X is far more competitive than rider Y. In other words, rider X would benefit more from a lower back angle than rider Y. The shoulder angle is also higher for the recreational rider with 82.11° in comparison to 79.77°, which makes rider Y stretch more.

Respective end-fit characteristics are in sheer contrast with the goals of both riders, the recreational rider's objectives primarily focusing on comfort and injury prevention and the professional rider focusing on performance. It can therefore be concluded that some fitters might pay (too) little attention to the specific training goals of their clients.

Table 2: Key values from the motion analysis, all values are in degrees, expect for KOPS [cm].

Test Person	Knee angle L	Knee angle R	Heel angle L	Heel angle R	KOPS	Back angle	Pelvic tilt	Shoulder angle
X	144.0	145.6	5.0	-5.0	0.0	39.1	-1.5	81.4
X	150.0	152.5	3.0	8.0	2.5	38.3	-0.7	81.6
X	150.2	150.7	-2.0	8.0	1.6	38.9	1.8	79.4
X	143.2	146.3	-2.0	8.0	2.7	40.0	1.4	77.4
X	146.9	149.3	0.0	10.0	1.2	39.6	3.4	78.3
X	152.4	154.5	1.0	8.0	1.6	37.8	1.0	80.8
X	147.3	148.2	1.0	10.0	4.0	39.6	6.4	75.1
X	148.8	150.0	0.0	9.0	2.7	38.0	4.4	79.1
X	144.2	144.8	-2.0	8.0	3.2	38.5	2.5	80.6
Y	146.7	146.2	2.0	-2.0	0.0	32.2	4.6	83.0
Y	146.3	145.3	6.0	4.0	3.0	34.8	1.4	81.3
Y	149.0	149.1	6.0	2.0	1.5	33.4	2.4	82.6
Y	151.3	150.3	8.0	4.0	2.0	33.9	3.4	79.8
Y	146.2	141.5	11.0	9.0	2.2	33.0	2.7	82.3
Y	142.8	140.6	6.0	6.0	1.5	32.5	2.5	85.7
Y	150.3	145.2	11.0	6.0	2.7	32.7	6.4	79.8
Y	148.6	148.0	9.0	4.0	1.5	31.8	5.7	83.1
Y	151.9	147.8	9.0	6.0	1.4	31.7	4.6	81.4

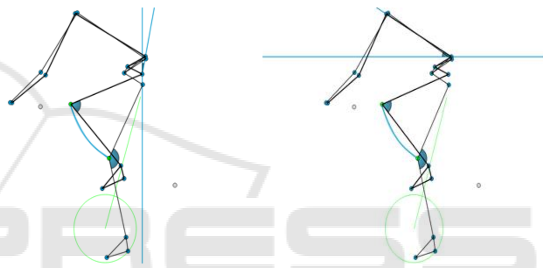

Figure 11: Left - pelvic tilt angle, right - back angle.

In the lower body there were less notable differences, rider X has on average 1.2 degrees higher knee angles (148.27 in regard to 147.06). The heel angles came out quite a bit lower for rider X (3.78 degrees in regard to 5.94), even though he has limited flexibility in his right ankle due to an injury in the past. Generally, 0 degrees heel angle are considered good, however this is also a personal matter, mainly depending on the pedaling technique and preference.

3.2.2 Comparison of Different Bike Fitting Studios

In this comparison the hypothesis is twofold. Firstly, the different bike fitting studios are compared to one another to see if the proposed end configurations result into similar knee, heel, shoulder and back angles as well as KOPS and pelvic tilt. Secondly, the end fits advised by the different bike fitting studios are analyzed to see if they take the customer's training goals into account. The hypothesis is that there could be larger differences in upper body, as the goals of the cyclists are very different. However, since more lower body rules-of-thumb exist, there should be lesser variability in lower body variables between the different bike fitting studios.

Upper Body:
For the upper body analysis, shoulder angle, pelvic tilt and back angle are considered. With regard to back angle, no consensus could be established comparing the results of the fits of each of the consulted studios. The average difference is 6° and as previously mentioned, it must be noted that the back angle is lower for the recreational rider, which is contrast with his athletic profile and training ambitions. For pelvic tilt and shoulder angle, the different bike fitting studios seem to have more of a general approach towards determining the ideal angle. All but one of the bike fitting studios have one of these two which are within a 2° range between the two riders. However, there is no studio which simultaneously has both of them within the 2° range. So, there is little consensus within the bike fitting studios as to what the ideal angles are in upper body, and even less between them. This was also mentioned in the hypothesis, however in contradiction to the hypothesis, the recreational rider is in a more aggressive position than the professional rider.

Lower Body:
Firstly, when comparing KOPS measurements for the different cyclists within the same studio, three studios fall within the acceptable error margin for both cyclists (1 mm). Secondly, for heel angles not only the left and right differences are compared but also the average of left and right maximal heel angles. The comparison for each side individually shows large differences between and within studios. This can be due to reduced flexibility in the right ankle of rider X, because he broke his ankle in the past and this is still visible when observing the cycling motion. This injury background was also observed during field tests using data of a double-sided power meter (Shimano Dura-Ace R9100-P). Advanced power statistics show Left-Right power balances which are far off (around 55/45) and are reporting higher pedaling smoothness for the left side. Therefore, left and right heel angles averages were calculated and analyzed. This results in five studios which offer a heel angle within a range of 2° for the different cyclists. Lastly, with regard to knee angles, three of the examined studios have a knee angle difference smaller than 3° between both cyclists for both the left and right maximal knee angle. And if the average of maximal left and right knee angle is considered, there are even four studios within the 2° margin. To conclude, heel angles and knee angles do not differ much, when comparing the two cyclists within the same bike fitting studio for at least four of the nine studios. But when comparing the studios to one another, the differences are often quite large.

3.2.3 In-depth Analysis for Each Test Person

In this chapter the different configurations, advised by the bikefit studios for each cyclist, are compared to one another.

Test Person X – Pro Cyclist:
For the pro cyclist, the average maximal knee angle is 148.27°. These are larger angles than expected, even five studios are above 149° and three out of those five are above 150°. The difference between highest and lowest maximal knee angle is 9.7°, so there is no real consensus for knee angles between fitting studios for the pro cyclist. The average left heel angle over the different studios is -0.67° which is to be expected, although the difference between the highest and lowest heel angle is 8° so no real consensus exists. The right heel angle is a much different story as our test person had a limited flexibility in his right ankle due to a previous injury. The average angle was 8.22° with a difference of 5°, it can be concluded that the limited flexibility does not allow this person to fully flex his ankle which results in a higher angle. For KOPS, the average between the studios was 2.17 cm and the differences were again quite large between studios with a maximal difference of 4 cm. The highest KOPS value is 4 cm which is considered to put a lot of stress on the knee joint. As previously mentioned, the upper body positioning is quite personal, the average back angle is 38.87°, the average pelvic tilt is 2.08° and the average shoulder angle is 79.30°. Again, there are quite big differences in these angles, but this is largely due to one specific outlier. Without this outlier there still exist differences of 2.2°, 5.9° and 4.2° respectively. Concerning symmetry and stability, there were no significant differences between the fits. This is probably due to the rider's better ability to adapt to these changes in configuration in comparison with the recreational rider. Conclusive for this chapter it is important to note that there is little to no consensus between the individual bikefitters. As will also be confirmed by the analysis of the recreational cyclist.

Test Person Y – Recreational Cyclist:
For the recreational cyclist, the maximal knee angle averaged over the different studios is 148.12°. This is quite large, even four configurations led to knee angles of over 149°. The difference between the

highest and lowest maximal knee angle is 9.7° and is a direct consequence of the large difference in saddle height between these configurations (2.2 cm) and saddle setback (1.8 cm). For heel angles, differences of 9° and 11° are present for left and right respectively between different studios. This is the consequence of the lower flexibility that is allowed in different configurations. Also, and in correspondence with our previous test person, the KOPS measurements show differences of 3 cm, with an average KOPS of 1.76 cm in the different configurations. The high value for KOPS can pose problems for the cyclist on the longer run, as this will put more stress on the patella and can result to knee overuse injuries. The upper body is, as mentioned before, a rather personal preference and in this case a direct result of saddle position adjustments. This is due to the fact that none of the fitters advised another stem length for this cyclist. It should be mentioned that large maximal differences existed between the fits (3.4 cm in saddle setback and 3 cm in saddle height). There were some studios which advised a similar saddle height or saddle setback, but no studios advised similar saddle height and setback simultaneously. However, these configurations are harder to compare as there was also no consensus in the cleat positioning, in contrast with person X by whom the cleats were positioned the same by every bike fitter. This can be due to the different cleat system; person X uses the Speedplay system which is hard to adjust as opposed to person X who used Shimano SPD-SL cleats which are easy adjustable. Lastly, it is remarkable that this rider's stability was highly variable for the different configurations. In only one particular end fit the rider was very stable on his bike as opposed to the other fits. This fit is also suggesting a position with the KOPS at 0 cm and the advised knee angles of +- 145 degrees, which might not be a coincidence.

4 CONCLUSIONS

The present study results indicate that the differences in bike fit end position between fitting studios were larger than expected. As it is often the case, the ideal value for a bike fit measurement will be somewhere in the middle of both extrema of the end fits. A difference of 2 cm in saddle height or fore-aft position of the saddle is certainly an adjustment that the rider will be very aware of. When making these drastic adjustments, the neuromuscular system will be addressed and loaded completely different.

As there still are large differences between the individual fitters, it certainly is important to focus on a qualitative education. The general rules of thumb, such as Knee Over Pedal Spindle (KOPS) for example, should be well known to the fitters. Additional scientific proof could be a trigger to use these rules and make them part of the general bike fitting procedure.

5 FUTURE WORK

Initial results show that there is indeed a broad range in the advised positions by the different bike fitters. However, before this research it was not clear that this range would be this broad. There are various possible explanations for this (i.e. used technologies, experience level, education background, …). These initials tests were done with a small group of subjects, additional test persons could possibly empower our findings. Still, even with this limited test group, it can be concluded that the bike fitting industry is indeed suffering from subjectivity.

Secondly, to analyze the different end fits, it would be interesting to make use of other systems apart from the Myontec Mbody and the Bioracer Motion system. Firstly, torque analysis could be a useful tool to analyze the pedaling motion. A perfect pedaling motion will have a 50/50 right/left distribution (and was shown to be not the case for our pro rider), as well as a small dead point in the revolution. With the use of torque analysis, it can also be shown during which phase of the pedal revolution the peak power is produced. Thirdly, in a good cycling position the saddle pressure will be evenly spread across the surface of the saddle with a relatively low peak pressure. Saddle pressure measurements were also executed by some fitting studios which used the GeBiomized system. Unfortunately, most of the saddle pressure results were not collected in the actual reports, but only told to the test persons during the fit.

A data-driven approach towards bike fitting has already proven to be useful (Braeckevelt, et al., 2018). Preliminary experiments focusing on saddle height optimization have been conducted and prove the feasibility of the proposed methodology. Saddle height is a determining factor in knee injuries (Bini, et al., 2011) and the outputted power (Peveler & Green, 2011). However, it is important to mention that saddle height optimization is only a small step in the bigger bike fitting process, as there are many other parameters that should be optimized (Gonzalez & Hull, 1989).

The proposed methodology for the saddle height experiments was to compare three different bike configurations (i.e., saddle too high, too low and the 'optimal' position) for different pairs of markers. An example of these spatio-temporal comparisons is shown in Figure 12. This graph shows the relation between the crank angle speed and the right knee Z speed over time. A good feature to track would be the occurrence of the minimum with regard to the crank angle. If the saddle is in a position that is too high, for example, the minimum occurs at a particularly lesser crank angle. Several similar additional features are evaluated on the Bioracer Motion dataset to determine the rate of true positives and false positives for each of the features. The lesser false positives, the higher the weight of this feature. In the end, a series of eight features (focusing on the left/right foot and knee movement in X/Y direction) are fed into a weighted feature sum, based on which the saddle height correction is suggested. This methodology results in a 100% correct saddle height up to an accuracy of 5mm for a test set of 40 fits.

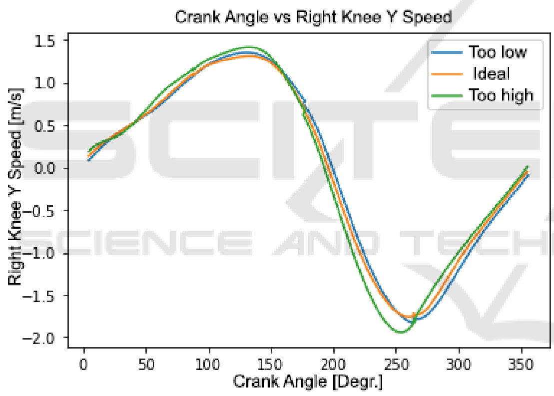

Figure 12: Knee speed in function of the crank angle (in degrees).

Lastly, research to prove or disprove some general rules of thumb, that have been used for decades, should be conducted. The rules have had a major impact on some of the end fits and almost every bike fitter uses at least one of those rules. When these can be proven, and data-driven bike fitting is further developed, a more objective manner of bike fitting will be made possible. This might have a huge impact on the current bike fitting landscape.

The final goal of our research is to have a fully autonomous bike fitting system, which can fit a cyclist with sufficient accuracy in a short period of time. This system will have a significant impact on the cycling world, as less knowledge will be required to successfully fit cyclists. However, it should be noted that competent bike fitters still play an important role fitting the professional cyclists and very specific clients, as well as to provide feedback for the data-driven bike fitting system.

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