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ORIGINAL ARTICLE

Effects of increasing physical load and fatigue on the biomechanics of elite cyclists

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ABSTRACT

In this study, we propose to expand the research on the biomechanics of cycling, including changes caused by riding at different intensity levels and fatigue, similar to training or competition. Six well-trained, experienced male road cyclists (27.17 ± 3.89 years; 180.41 ± 5.31 cm; 75.23 ± 4.91 kg) with 8.3 ± 4.85 years of (professional) experience in road cycling underwent a lactate test, starting with 100 W and an increment of 20 W every 3 minutes until total exhaustion. Afterward, subjects drove an increment of 50 W every 3 minutes, starting again with 100 W and ending with 250 W (post-test). Changes in position were recorded via 2D video analysis. We found that with higher power output relative to the individual anaerobic threshold (IAT), the joint angles changed. No significant differences were present for the pre–post comparisons of the examined angles, which should map the influence of fatigue ($p > .05$). Future research should try to observe cycling movement in more realistic settings, such as cycling-specific fatigue or during an outdoor ride, as the biomechanics under these conditions are of particularly high relevance for the athletes. Overall, the results suggest performing bike fitting more individually and in more realistic situations or setting.

Keywords: Performance analysis of sport, Physical conditioning, Bike fitting, Movement analysis, Cycling, Joint overuse, Joint misloading, Biomechanics.

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INTRODUCTION

In road cycling, it is important to ride as economically as possible; over the course of a cycling stage, any energy saved might help to improve overall competition performance. Besides this, an optimal position on the bike plays a crucial role in both enhancing performance and reducing the risk of non-traumatic injuries (overuse) (Bini, Hume, Croft & Kilding, 2014; Dettori & Norvell, 2006).

Most research has focused on evaluating the efficiency of a seating position but with measurements at submaximal load perceived as habitually comfortable (Bini, Hume & Croft, 2014; Priego Quesada, Kerr, Bertucci & Carpes, 2018). However, it is unclear whether this procedure represents a realistic cycling situation in the field. If relevant angles of the lower body are dependent on different riding intensity levels and fatigue status, the determination of a position at a fixed submaximal load would underrepresent the real complexity. The transferability to high-intensity loads during a competition on the road or during sprints as they are ridden in track cycling seems substantially limited. There is only one prior study known to us that investigated the changes in sitting position during high-intensity 6s sprints (Bini, Daly & Kingsley, 2020). Such changes may lead to non-physiological positions and a potential increase in non-traumatic injury prevalence, which usually correlates with the level of fatigue. Fatigue leads to slower and less coordinated muscle activation, changing the activation pattern and, therefore, the movement (Abbiss & Laursen, 2005; Billaut, Basset & Falgairette, 2005), setting a risk for overuse injuries (Galindo-Martínez, López-Valenciano, Albaladejo-García, Vallés-González & Elvira, 2021). This injury prevalence is often linked to the knee (Bini & Bini, 2018; Clarsen, Krosshaug & Bahr, 2010) and lower back (Clarsen et al., 2010). Knee pain is often associated with a small knee angle, which leads to a medial rotation of the femur, lowering the contact point of the joint and thereby increasing the patellofemoral pressure (Bini et al., 2018). Proper bike fitting can prevent this misloading leading to overuse of the knee joint (Bini, Hume & Croft 2011) and can help to increase the efficiency of the movement (Bateman, 2014).

According to the above-mentioned aspects, there is a lack of research regarding the influence of different riding intensity levels and fatigue on lower-body biomechanics while riding. Therefore, we want to examine (1) whether different riding intensity levels relative to the individual anaerobic threshold (IAT) result in changes in the biomechanics of the lower body. Furthermore, we wish to evaluate (2) whether lower-body biomechanics while riding before (pre-test) and after an all-out treatment in a fatigued state (post-test) are different.

MATERIALS AND METHODS

Subjects and data acquisition

For this research, six well-trained, male road cyclists (27.17 ± 3.89 years; 180.41 ± 5.31 cm; 75.23 ± 4.91 kg) with 8.33 ± 4.85 years of (professional) experience in road cycling underwent body fat and body composition measurement using the InBody 770 (InBody Europe, Eschborn, Germany) system (body fat: 11.87 % ± 3.2; skeletal muscle mass: 37.75 ± 3.22 kg; lean leg mass: 20.57 ± 2.14 kg), a posture analysis (Balance 4D, Paromed, Neubeuern, Germany), and a dynamic 2D bike fitting. The sample size of this study was selected based on Bateman (2014).The subjects were recruited through contacting the team. The left and right body sides were both analysed to allow a comparison and additional validation of the results. Therefore, videos were recorded for both sides in the sagittal plane during the test. Prior to the study, the riders underwent a dynamic 2D analysis on the bike. For all subjects, the knee angle in the 90° crank position and the knee position in relation to the pedal axis met the selected reference values (knee angle: 110°–115° in the 90° position of the crank; axis of the knee vertically above the pedal axis (Bini et al., 2016)). The 90°

position (9 o'clock position) was selected for (pre-) evaluation, as there are greater forces present in the patellofemoral area than in the 180° position. Further, this position shows a higher reliability (Bini & Hume, 2016; Ericson & Nisell, 1987). The 180° position was additionally used for the following analysis, as it is most commonly used in bike fitting practice, as well as in other studies (Bini et al., 2011; Ferrer-Roca et al., 2011; Swart, & Holliday, 2019). After pre-evaluation of the position on the bike, subjects performed a lactate stepwise incremental test, starting at 100 W with an increment of 20 W every 3 minutes until total exhaustion (Wahl, Manunzio, Vogt, Strütt, Volmary, Bloch &Mester,2017). Post-treatment, it was controlled that every subject showed lactate values exceeding 8 mmol/l at the point of termination. Therefore, according to de Marées (2003), it can be assumed that a high fatigue status was present.

After the exhaustion, the cyclists had a short period of 5 minutes of active regeneration with low resistance selected as habitually comfortable. After this regeneration phase, the subjects drove an increment of 50 W every 3 minutes, starting again with 100 W and ending with 250 W.

Measuring method

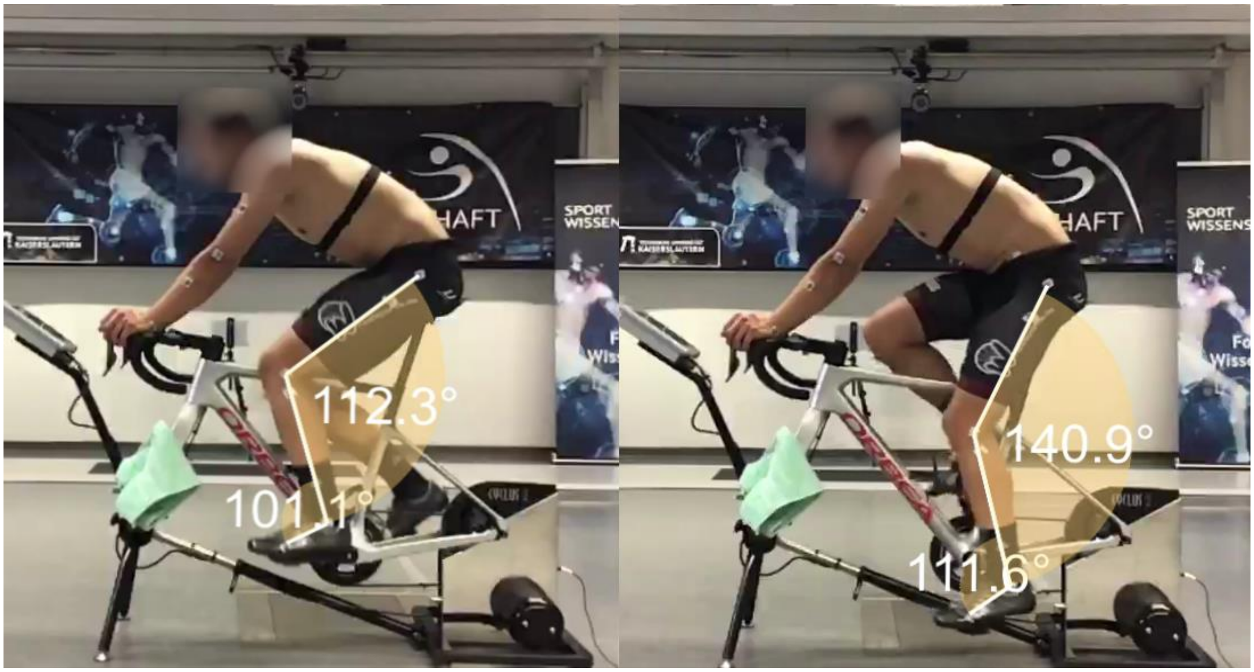


Figure 1. Measuring procedure and angle definition.

For the lower-body biomechanics, we focused on knee and ankle angles as shown in Figure 1; these angles are reliably measurable in 2D analysis, were observed in most of the previous studies, and are of high practical relevance (Swart et al., 2019). The 2D analysis was performed by simultaneously filming at 120 fps with two iPads (7th generation, Apple, Cupertino, USA/CA) that were positioned at a standardized distance perpendicular to the cyclists, as suggested by Fonda, Sarabon and Li (2013). The calculation of the joint angles based on the 2D video data was dependent on four markers for each body side placed on the metatarsophalangeal joint, the lateral malleolus, the lateral part of the articulatio genus, and the greater trochanter. Marker placement and angle calculation were performed according to Bini et al. (2014). Lactate was measured using a lactate scout (EKF Diagnostics, Barleben, Germany), and heart rate was measured using a Polar V800 (Polar Electro GmbH, Büttelborn, Germany) with the matching pulse sensor. Angles were determined using Dartfish ProSuite 8.0 (Dartfish, Freiburg, Switzerland) (see Image 1). Six images for each measurement time point (three images at 90° plus three images at the 180° position) were selected. The mean values of the three images separately for the 90° and 180° positions were used for further calculations.

Data pre-processing and analysis method

To allow a comparison of the subjects relative to their (a) fitness level and (b) initial individual posture on the bike, an individual standardization was performed. Therefore, (a) the power outputs relative to the individual anaerobic threshold (IAT) were determined. To answer the question (2), cubic spline interpolation was additionally applied to enable a comparison of the angles relative to the same relative power output. Furthermore, (b) standardized angles were calculated by dividing each angle by the mean angle for the measurements under the IAT (only for (1); this was based on the assumption that the angles below the IAT are likely to be relatively similar due to lower fatigue).

Due to the relatively small sample size, inferential statistical methods were inappropriate. Therefore, an idiographic analysis of the individuals was performed. In order to further discuss the corresponding results using objective metrics, (1) regression equations of the lower-body biomechanics of the standardized angles as a function of the relative power output were reported. Therefore, outliers were identified and removed if values reached three times the interquartile range. Further, to discuss question (2), a dependent t-test was additionally performed to compare the values between the pre- and post-conditions for intensity levels of 60% and 80% of the IAT. The underlying assumptions were checked and confirmed before the calculations. It should be emphasized again at this point that these calculations are intended to support the idiographic analysis and must be interpreted with caution. Calculations were performed using Python (Python Software Foundation, Wilmington, DE, USA) and SPSS Statistics (version 16, SPSS Inc., Chicago, USA).

RESULTS

The test was terminated after total subjective exhaustion (power output: 373.3 ± 37.7 W; min: 320 W; max: 440 W; lactate: 11.58 ± 2.82 mmol/l min: 8.1 mmol/1 max: 15.4 mmol/l; heart rate: 186 ± 16 1/min). The results showed side asymmetries for the knee and foot relative to the IAT. For riding at 80% IAT, the lowest mean absolute difference was found for the knee in the 180° position (2.98 ± 1.31°). The highest mean absolute side difference was found for the foot in the 90° position (5.89 ± 4.85°).

Changes with increasing power output

The visualizations of the changes in the knee and foot angles during progressive intensity increase are presented in Figures 2 and 3. Looking at the quality of the fit (R^2) shows that for the left and right foot in the 180° position, the fit was the worst ($R^2 < 0.25$). Further, the right knee in the 180° position showed a noticeably low R^2 ($R^2 = 0.15$) compared to the other models ($R^2 \geq 0.37$), which can be classified as a strong effect according to Cohen (Ellis, 2010). Visually, between-subject variability increased for riding intensities over the IAT, and the changes seem highly individual.

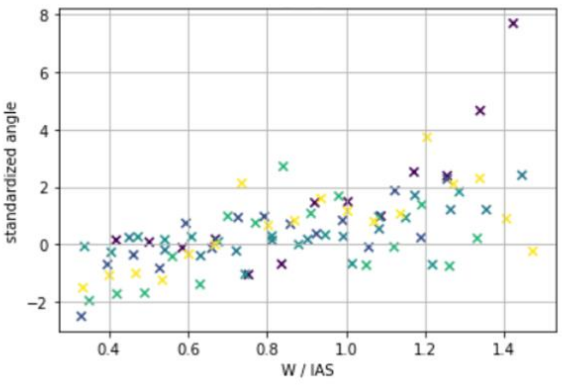
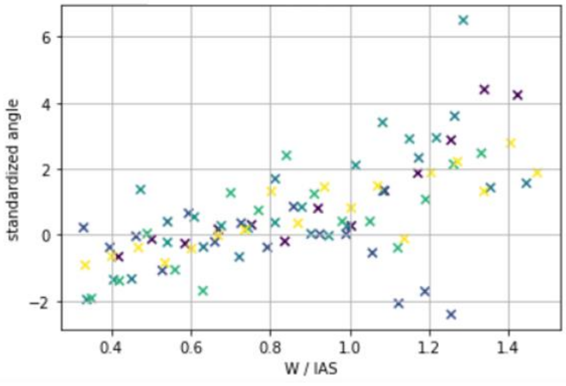
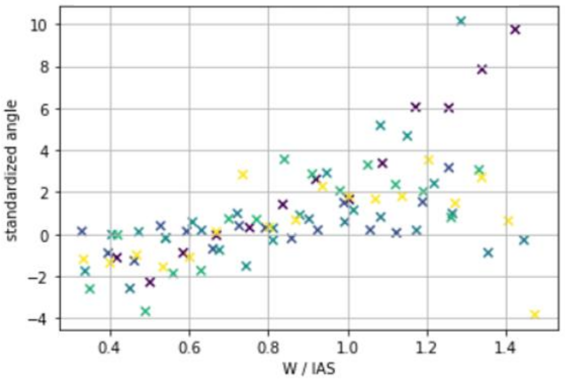
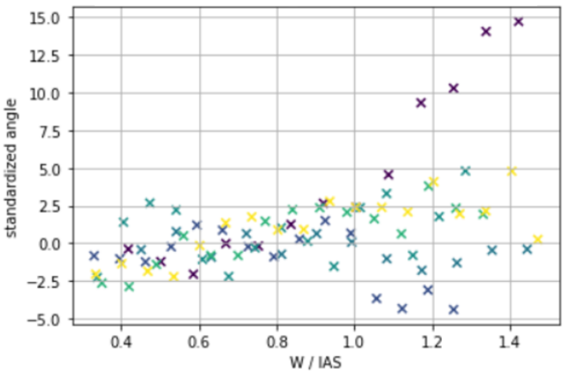
Left knee angle at 90° crank position	**Right knee angle at 90° crank position**
	
F(1,85) = 55.47, *p* < .001; R² = .40; y = -1.719 + 2.497*x	F(1,84) = 74.79, *p* < .001; R² = .47; y = -2.039 + 3.057*x
Left knee angle at 180° crank position	**Right knee angle at 180° crank position**
	
F(1,83) = 64.70, *p* < .001; R² = .44; y = -2.903 + 4.383*x	F(1,84) = 14.85, *p* < .001; R² = .15; y = -2.061 + 3.059*x

Figure 2. Changes in knee angle relative to each subject's IAT. Individual standardization was performed. A knee value of 0 represents the mean angle of the individual measurements under the IAT. The colour coding differentiates the individual athletes.

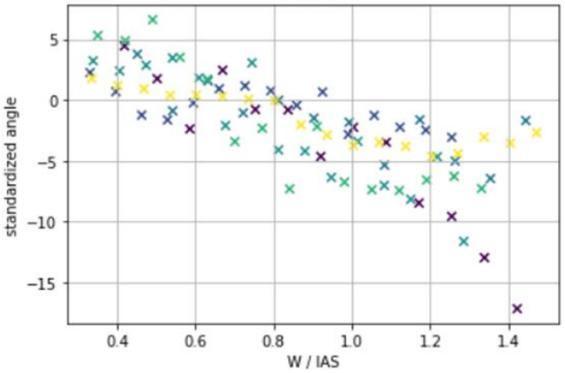
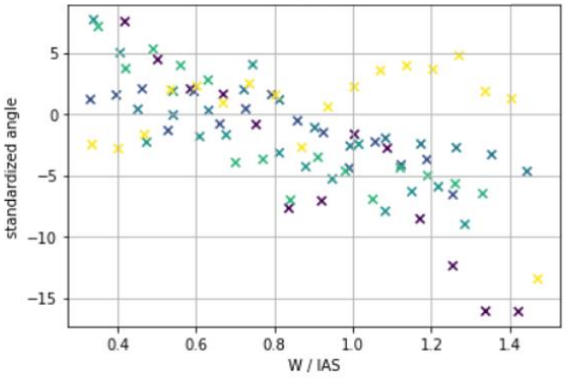
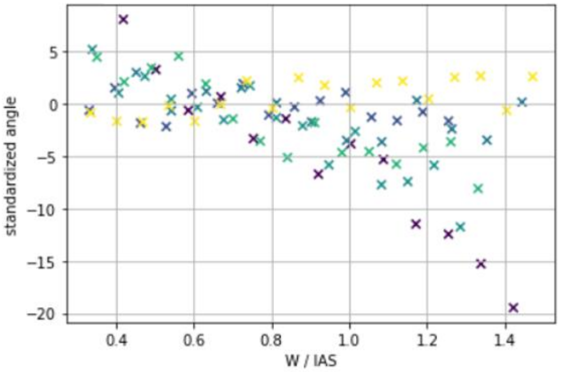
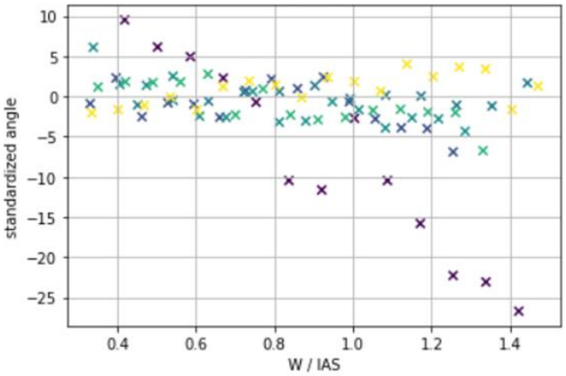
Left ankle angle at 90° crank position	**Right ankle angle at 90° crank position**
	
F(1,85) = 124.74, $p < .001$; $R^2 = .59$; y = 6.277 - 9.504*x	F(1,86) = 49.78, $p < .001$; $R^2 = .37$; y = 6.306 - 9.135*x
Left ankle angle at 180° crank position	**Right ankle angle at 180° crank position**
	
F(1,85) = 27.64, $p < .001$; $R^2 = .25$; y = 4.078 - 6.243*x	F(1,83) = 9.00, $p = .004$; $R^2 = .0.10$; y = 2.487 - 3.769*x

Figure 3. Changes in foot angle relative to each subject's IAT. Individual standardization was performed. A foot value of 0 represents the mean angle of the individual measurements under the IAT. The colour coding differentiates the individual athletes.

Fatigue-introduced differences

The pre- and post-test comparison showed no differences for the knee and foot angles ($p > .05$). Table 1 shows the respective results.

Table 1. Mean differences between pre- and post-test for the knee and foot angles while riding at intensity levels of 60% and 80% of the IAT.

	90		**180**	
	Left	**Right**	**Left**	**Right**
Knee 60 % IAT	0.58 ± 0.63 *p = .076*	1.41 ± 2.50 *p = .226*	-0.13 ± 1.76 *p = .867*	1.24 ± 3.15 *p = .380*
Foot 60 % IAT	-0.49 ± 3.24 *p = .728*	0.64 ± 2.55 *p = .565*	0.31 ± 3.09 *p = .816*	0.44 ± 4.36 *p = .815*
Knee 80 % IAT	0.32 ± 1.00 *p = .465*	1.22 ± 1.78 *p = .156*	-0.26 ± 1.54 *p = .695*	0.63 ± 2.94 *p = .623*
Foot 80 % IAT	0.75 ± 1.96 *p = .392*	1.11 ± 2.82 *p = .379*	0.82 ± 2.79 *p = .502*	1.44 ± 3.23 *p = .326*

DISCUSSION

The current study's results indicate that with higher power output relative to the IAT, the joint angles change (1). An additional validation is given due to the presence of similar characteristics and effects for both body sides. Overall, the knee angles increase, while the foot angles decrease. These findings are in accordance with the results of other research (Galindo-Martínez et al., 2021; Swart et al., 2019) in which it was stated that the muscles of the lower leg (M. gastrocnemius, M. soleus, M. tibialis anterior) are the first to show differences in range of motion and activation. Regarding the targeted muscles, M. gastrocnemius and soleus seem to be the first to reach exhaustion, resulting in a decrease in the ankle angle and, consequently, an increase in the knee angle (Swart et al., 2019). Under the IAT, the change trend of the respective angles appears almost linear, while with higher levels of fatigue, the interindividual differences change drastically, and the change seems to be nonlinear. This may be caused by different muscle exhaustion and compensation mechanisms, which seem to be highly individual among the subjects due to their individual physical capacities. Further, additional factors, e.g., pain (two subjects mentioned slight pain in the perineum at the end of the test), limited flexibility, or the presence of side asymmetries, might have resulted in highly individual responses. Nevertheless, the individuality of the changes underlines the recommendation of bike fitting under more realistic conditions.

As a possible reason for the low R^2 value for the foot in the 180° position, changes in the angles might be highly individual due to possible differences in muscular status. Further research should evaluate potential relationships. The low fit of the right knee in the 180° position might be due to the presence of side asymmetries, which could possibly be explained by the presence of scoliosis in two subjects.

The pre–post comparison (2) showed that there were no differences present for the knee and foot angles between the rested and fatigued states after the all-out protocol. This may be due to the experience level of the cyclists, who potentially have the ability to (a) recover from exhaustion very quickly or (b) take a position that is economical even in highly fatigued states. Counter to these findings, the works of O´Bryan, Brown, Billaut and Rouffet (2014) and Billaut et al. (2005) explain that with increasing fatigue, intermuscular coordination and, therefore, power output decrease. The lack of differences in the pre–post comparison in the present study is also supported by the findings of Froyd, Milles and Noakes (2013), which stated that neuromuscular function is recovered very quickly (ca. 2 min after termination of the exercise). For more reliable determination of the extent of muscle fatigue and the cause of exercise termination, as well as the time course of central and peripheral fatigue, the present study should be supplemented by measurements via EMG (Hug, Laplaud, Savin & Grelot, 2003) and pressure sensors or special ergometers (Doyle-Baker, Temesi, Medysky, Holash & Millet, 2018). Further research should try to evaluate this aspect, e.g., through more precise evaluation of the level of fatigue and a fatigue that is more specific to that achieved during cycling.

Furthermore, the results show the presence of side asymmetries for the knee and foot. Possible reasons for this might be scoliosis or muscular imbalances. Looking at the posture measurements of the subjects indeed showed that scoliosis was present for two subjects. This also highlights the importance of analysing both body sides in addition to the general posture while performing bike fitting.

It should be mentioned that the fatigue in the present study after the lactate diagnostics probably does not correspond to the athletes' fatigue in practice, e.g., after a race. The extent of central and peripheral fatigue varies with intensity and duration (Thomas, Elmeua, Howatson & Goodall, 2016). Therefore, other results could be obtained, for example, when examining pre–post position after a long cycling race. Further research should address this in the future.

The study has some limitations, but the study was planned as an exploratory pilot study; therefore, these limitations are justifiable from our point of view. Of course, further work is necessary to check the results. The limitations relate to the following points: The representation of the sample is limited, because these were only male, professional, well-trained cyclists with years-long experience in road cycling. The results of this study may or may not be applicable to female, amateur, or recreational cyclists (e.g., amateurs may show greater differences in movement when fatigued). In addition, the sample size is very small, so for generalizable results, further research should aim for an increased sample size and to include cyclists of different performance levels and disciplines.

A few factors, such as the rotation of different body parts, the tracking of the markers, and, therefore, the movement of these body parts, cannot be determined via 2-dimensional recording. However, these lateral and rotational movements could be a factor in causing non-traumatic injuries. For future works, 3D analysis should be considered for movement analysis.

CONCLUSION

The present study's results show that with increasing load, the position and the posture on the bike change; this may be a reason why cyclists have a greater risk of developing a poor posture (Muyor, López-Miñarro., & Alacid, 2011). Therefore, it seems necessary to perform additional strength and posture training (with special focus on the M. erector spinae, the Mm. rhomboidei, the abdominal muscles, and the M. trapezius) to be capable of holding an optimal position (especially when an aerodynamic position is targeted) on the bike for as long as possible. Referring to the review by Streisfeld, Bartoszek, Creran, Inge, McShane and Johnston (2016), the authors hypothesize that cyclists change their position during loads to maintain an optimal force–length–velocity relationship of the muscles. Therefore, and to control the risk of non-traumatic injuries by maximal performance at the same time, it is indispensable to perform function and muscle tests to see which muscles and performance areas need to be trained. Furthermore, the results suggest that it is necessary to perform dynamic bike fitting involving real-world riding situations (e.g., in usual competitive performance or with usual competitive characteristics) to determine the positions during high-intensity or prolonged rides. This holds the potential both to improve cycling performance through a maximization of economy and to prevent non-traumatic injuries. Empirical examination of the topic must be continued in order to develop clearer, scientifically based recommendations for sports practice in the future.

AUTHOR CONTRIBUTIONS

Bartaguiz, Dindorf conceived and designed the experiments; Bartaguiz, Dully performed the experiments; Dindorf and Fröhlich. analysed the data; Fröhlich and Becker contributed materials/analysis tools; Bartaguiz, Dindorf, Dully, Becker and Fröhlich wrote the paper.

SUPPORTING AGENCIES

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICS STATEMENT

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by "*Technische Universität Kaiserslautern*" for the project conducted. Informed consent was obtained from all subjects involved in the study.

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