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Vibrotactile Feedback for Correcting Aerodynamic Position of a Cyclist

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Abstract

Guidance to maintain an optimal aerodynamic position is currently unavailable during cycling. This study used real-time vibrotactile feedback to guide cyclists to a reference position with minimal projected frontal area as an indicator of aerodynamic drag, by optimizing torso, shoulder, head and elbow position without compromising comfort when sitting still on the bike. The difference in recapturing the aerodynamic reference position during cycling after predefined deviations from the reference position at different intensities was analysed for 14 participants between three interventions, consisting of 1) vibrotactile feedback with a margin of error of 1.5% above the calibrated reference projected frontal area, 2) vibrotactile feedback with a margin of 3%, and 3) no feedback. The reference position is significantly more accurately achieved using vibrotactile feedback compared to no feedback ($p < 0.001$), but there is no significant difference between the 1.5% and 3% margin ($p = 0.11$) in terms of relative projected frontal area during cycling compared to the calibrated reference position (1.5% margin -0.46 ± 1.76%, 3% margin -0.01 ± 2.01%, no feedback 2.59 ± 3.29%). The results demonstrate that vibrotactile feedback can have an added value in assisting and correcting cyclists in recapturing their aerodynamic reference position.

Keywords: vibrotactile feedback, aerodynamics, indoor training bike, cycling, frontal area

Introduction

In cycling, it is essential to find an aerodynamic and biomechanical optimal position on the bike to achieve maximal comfort and excellent performances during training and racing[1,2]. Firstly, capturing an optimal biomechanical cycling position is crucial since cycling is a sport with several repetitive movements under an extensive load. Inappropriate biomechanical cycling posture and movements such as pedalling asymmetry can lead to an increased risk and impact of injuries such as lower back pain[3] or decreased exercise intensity[4]. Therefore, adjustments in saddle height[5] and handlebar height[6] are important in injury prevention as well as in performance optimization.

When defining a reference cycling position and movement, it is important to find a consideration between biomechanical and aerodynamic properties. However, it is not opportune to optimize both separately since they also affect each other[1,7,8]. At high speeds (> 46 km/h), the aerodynamic resistance is the main influence on cycling performance. At lower speeds, the dominant factor is dependent on the type of cycling effort (energy expenditure or efficiency)[9]. About 90% of the total resistive force during cycling is due to wind resistance[10], where the majority of aerodynamic drag is induced by the rider[11,12]. Optimizing the aerodynamic cycling position can lead to a gain in velocity, where the magnitude of profit is different for each cyclist[13].

The main problem is that after capturing the aerodynamic reference position for an individual cyclist, there is no control over the maintaining of this position during training or racing.

Therefore, this study focuses on the opportunities to provide real-time feedback on the predefined aerodynamic reference cycling position in training situations. The aerodynamic reference cycling position can be defined as the position with minimal aerodynamic drag and is described as a posture where the torso approaches an angle of 4° relative to the ground with shrugging the shoulders in and tucking the head down on a time trial bike[9]. The aerodynamic reference position

on a road bike has identical requirements, with additionally the hands on the handlebar drops by bending the elbow to 90° and keeping the forearms parallel to the ground and close to the body[14], which has the biggest advantage in specific road cycling circumstances such as in a breakaway[15].
The aerodynamic reference position for an individual can be analysed by wind tunnel experiments, using projected frontal area calculation or using computational fluid dynamics (CFD) simulations. By multiplying the projected frontal area with the drag coefficient, which is the dimensionless quantity that depends on the shape and surface of an individual, the method using the projected frontal area calculation provides a first-order estimate of the aerodynamic resistance of cyclists. The calculation of the projected frontal area can be accomplished using inexpensive methods in contrast to the other techniques.[10]

The projected frontal area is the area of the cyclist and the bike which is visible from a frontal observation and is dependent on body height, body mass, position on the bike and the equipment used. This method uses a photograph to calculate the projected frontal area, which means that the selection of an appropriate camera and calibration procedure is required to allow a reliable estimation of the aerodynamic reference cycling position.[10]

In order to provide feedback on the aerodynamic reference position, previous research showed that vibrotactile feedback is an elegant method to give instructions on posture-related tasks in real-time, with minimal latency[16]. Vibrotactile feedback is defined as the monitoring and steering of the posture and movement of people by applying vibrations on the skin through actuators. The perception of vibrotactile cues is guaranteed during sports without a decrease in recognition of the signals at higher levels of physical effort[17–19]. When using vibrotactile feedback, it is recommended to use one vibration signal to avoid distracting the athletes from their main focus[20]. Previous results showed that vibrotactile cues are well perceived for the thighs and the spine, but that vibrotactile feedback on the spine is preferred to guide cyclists to the most aerodynamic position[17].

This study hypothesizes that vibrotactile alerts can assist and correct cyclists in (re)capturing a desired aerodynamic reference cycling position. Therefore, this study aimed to investigate the accuracy of (re)capturing the aerodynamic reference position using vibrotactile feedback compared to no feedback.

Materials and Methods

Participants

The study included 14 amateur and competitive but non-elite cyclists to evaluate the differences in effect of vibrotactile feedback compared to no feedback since both groups have different experiences in capturing an aerodynamic reference cycling position. Sample size calculations (G*Power, version 3.1.9.4) revealed that a sample of ten participants would be sufficient to detect a difference between vibrotactile feedback and no feedback, with statistical power 0.95 and Type I error probability, associated with the test of this null hypothesis, 0.05. The study has been approved by the combined Ethical Committee of the University Hospital Antwerp and University of Antwerp (reference B300201629562) prior to starting the study. An informed consent with the information about the test protocol was signed by all participants. During the experiments, the participants wore a cycling suit, helmet, and heart rate monitor band. If available, participants used their time trial bike, since the aerodynamic drag is the dominant factor during time trials[10,11], if not they did the experiments on their road bike.

Indoor training bike system

The used training bike system is a patented[21] system to simulate real-world cycling experience which consists of 1) a smart trainer (Wahoo KICKR, Wahoo Fitness) to real-time load the power resistance 2) a camera (Intel® RealSense ™ depth camera D415, Intel Corporation) to calculate the projected frontal area and 3) a vibrating element (Vibration Motor, SparkFun Electronics) to provide vibrotactile feedback (Figure 1).
The indoor training bike system generates realistic resistance for an equivalent cycling experience as in outdoor training situations. The real-time power load mimics combined effects of air resistance, body position and velocity, and is constantly updated using Python 2.7.0 Release, at 10Hz, as function of simulated air resistance and simulated velocity. Air resistance directly depends on the cyclist's body position and is therefore simulated by calculating the projected frontal area of both the cyclist and the bike as an indicator for the aerodynamic drag[10] using camera images. The camera registers the frontal view of the participant (Figure 2a) and calculates the projected frontal area using pixel calculation and depth correction (Figure 2b) after calibrating it using a calibration frame with a known area and defining the desired measuring field of the participant and bike.
Simulated velocity is directly retrieved from the rear wheel rotation. Both drag and velocity are tuned to an adaptable resistance using an estimation of the power resistance based on the projected frontal area, the mass of the participants and bike and average coefficients of rolling resistance and drag[22–24] as in equation (1) and is automatically loaded to the smart trainer which can provide variable power load.

$$P = 1.053 * v * (0.03 * m + 0.615 * PFA * v^2) (1)$$

In this equation, 'P' is the power resistance in Watt, 'v' the velocity in m/s, 'm' the mass in kg and 'PFA' the projected frontal area in m^2. As such, the cyclists can directly feel the effect of their body position, and changes thereof, on their performance as it occurs in outdoor situations. It thus provides a safe way to monitor and optimize cyclist's behaviour in order to capture an aerodynamic reference cycling position.

Vibrating element

Furthermore, when participants exceed the projected frontal area captured in the aerodynamic reference position, vibrotactile feedback is applied to the C7 in the neck, since previous studies showed that this location is preferred to remind participants of their reference position (Figure 1b)[17]. The vibrating element can be activated wirelessly using an Arduino Feather 32u4 Bluefruit LE and HC-12 module, which is powered by an 850 mAh Lithium-Ion Battery. The current system enables us to investigate the opportunities to provide vibrotactile feedback on the aerodynamic reference cycling position using an indoor training bike system.

Procedure

This study analysed the effects of vibrotactile alerts on guiding cyclists to a desired reference position, in a closed-loop feedback system using the indoor training bike system. The reference position was determined as the position with minimal projected frontal area, using optimal torso, shoulder, head and elbow position[9,14], and a comfortable feeling on the bike as indicated by the participants. The reference position was calibrated for each participant individually before starting the experiments using 30 images to calculate the reference projected frontal area.

The study was a randomized controlled study and consisted of a comparison between three interventions to assist participants in retaining their aerodynamic reference position during cycling. In one intervention, the participants were provided with vibrotactile feedback if they exceeded a margin of 1.5% above the reference projected frontal area, the second intervention supplied vibrotactile feedback with a margin of 3% and in the last intervention, the participants received no feedback on their position, which was used as a control intervention. The margin of error of 1.5% and 3% above the reference projected frontal area was used to provide accurate and comfortable corrections for not optimal positions, without irritating participants by repeatedly providing vibrotactile feedback due to minor deviations. The sequence of the three interventions was random to eliminate training effects in the reference position.

For all three interventions, the participants were instructed to follow a 12-minute long protocol, which alternated periods of one minute in the reference position with periods where the participants were instructed 1) to sit upright with their hands on the base bar of the time trial bike handlebar or the hoods for the road bike as for taking a turn, and 2) to come out of the saddle simulating a climbing effort (Figure 3) (Table 1). Vibrotactile feedback was only applied during the reference periods and not during sitting upright and standing. Participants were allowed to change cadence and gear and were only instructed to respect heart rate zones of 70% and 80% of the maximal heart rate, which were determined using an ergometric step test to ensure standardized comparisons between participants during the experiments. The ergometric test started with an initial load of 75 W, followed by an increase of 0.5 W/kg body weight every three minutes, until exhaustion.

The heart rate zones of 70% and 80% of the maximal heart rate were used to simulate endurance training and to maintain the focus on the different intensities instead of the position. The 70% heart rate zone indicated a heart rate between 67.5% and 72.5% of the maximal heart rate and the 80% zone represented a heart rate between 77.5% and 82.5% of the maximal heart rate. The power was already automatically loaded on the smart trainer based on the projected frontal area calculation and could not be used as an input parameter to apply a similar relative effort for all participants.

Statistical Analysis

The accuracy of recapturing the reference position was compared between the three interventions. For each reference period (see * in Table 1), both the absolute and relative reference projected frontal area was calculated. The absolute projected frontal area in the reference periods was used to calculate the effect size, computed as Cohen's d[25], between interventions with and without vibrotactile feedback. The relative reference projected frontal area was the difference between the projected frontal area during the reference periods and the calibrated reference projected frontal area before starting the experiments divided by the calibrated reference projected frontal area. The average projected frontal area was calculated from the data collected between the 20th and 50th second of each minute-long reference period, to eliminate errors induced by changing positions.

The repeated measures ANOVA combined with Bonferroni post-hoc analysis investigated the differences in relative reference projected frontal area between the three interventions and the influence of the sequence in which the interventions were performed. The difference in the number of vibrations between the 1.5% and 3% margin was investigated using the Paired Sample T-Test.

Results

Participants

All 14 participants were male and had an age of 27.7 ± 11.1 years, a height of 177 ± 7 cm and a weight of 69.1 ± 9.9 kg. Seven participants were competitive cyclists with an average maximal power achieved during the ergometric step test of 348 W, the amateur cyclists had an average maximal power of 317 W. The participants had 9.8 years of cycling experience and trained 9.6 hours per week (13.4 hours for competitive cyclists, 5.9 hours for amateur cyclists). Eight participants performed the experiments using their time trial bike (three of them were competitive cyclists, five amateur cyclists), six used their road bike (four of them were competitive cyclists, two amateur cyclists).

Effect of three interventions on projected frontal area

During the reference periods, the average absolute projected frontal area is 0.324 ± 0.040 m^2 for the 1.5% margin, 0.326 ± 0.040 m^2 for the 3% margin and 0.331 ± 0.044 m^2 for the no-feedback intervention, with an effect size of 0.15 between interventions with and without vibrotactile feedback. The difference in absolute projected frontal area is 0.007 ± 0.011 m^2 between no-feedback and the 1.5% margin and 0.005 ± 0.010 m^2 between no-feedback and the 3% margin. The average absolute projected frontal area is 0.353 ± 0.042 m^2 for participants with a road bike and 0.302 ± 0.012 m^2 for participants with a time trial bike.
The relative reference projected frontal area for the vibrotactile feedback interventions is -0.46 ± 1.76% for the 1.5% margin and -0.01 ± 2.01% for the 3% margin, where it is 2.59 ± 3.29% for the no-feedback intervention.
The relative reference projected frontal area is significantly higher for the no-feedback intervention compared to the vibrotactile feedback interventions ($p < 0.001$). There is no significant difference between the 1.5% and 3% margin intervention ($p = 0.11$). Figure 4 shows the difference between the 14 participants for the three interventions. The sequence in which the interventions were performed has no significant effect on the differences in relative reference projected frontal area between the three interventions ($p = 0.10$).

Effect of margin of error on number of vibrations

The Paired Sample T-Test shows a significantly higher number of vibrations during the reference periods for the 1.5% margin intervention compared to the 3% margin intervention (1.5% margin 0.45 ± 0.75 vibrations/second, 3% margin 0.24 ± 0.45 vibrations/second, $p < 0.001$).

Discussion

Effect of vibrotactile feedback on projected frontal area

The main outcome of this study is that it is significantly more efficient to recapture the aerodynamic reference cycling position using vibrotactile feedback compared to no feedback, which means that it is difficult to recapture a predefined aerodynamic reference position without any guidance. This study proves that vibrotactile feedback is an elegant method to correct and assist cyclists in recapturing their aerodynamic reference position[16].

Both the relative and the absolute reference projected frontal area are similar for the of 1.5% and 3% margin. Figure 4 demonstrates that the preference for the 1.5% or 3% margin is dependent on the individual participant. Therefore, it is difficult to define an optimal margin of error above the aerodynamic reference position wherein no feedback is required for all participants. Some participants prefer strict and accurate corrections as with the 1.5% margin, while this can be rather annoying for others due to continuous providing vibrational cues, which was confirmed orally by the participants. For cyclists moving their torso during cycling effort or amateurs with less cycling experience, a margin of 3% is recommended rather than a margin of 1.5%.

Considering the absolute reference projected frontal area, an average decrease of 0.007 m^2 for the 1.5% margin and a decrease of 0.005 m^2 for the 3% margin is obtained compared to the no-feedback intervention. Converting these values of projected frontal area to power output using equation (1) induces a gain of 8 W (3% margin) to 12 W (1.5% margin)[22–24], which is a speed increase of 0.2 to 0.3 kilometres per hour and a time gain of 15 to 23 seconds for a 50-kilometre long time trial for an average rider. This is a constructive result since each minimal improvement in aerodynamic drag can have a considerable added value in competitive cycling.

The results in Figure 5 illustrate that the calibrated reference position in this study generally was a realistic but challenging approach of the aerodynamic reference cycling position since it was possible to recapture and maintain this position using vibrotactile feedback during different intensities of cycling effort, where it was difficult to recapture and maintain it without any guidance.

Furthermore, there is no significant effect of the sequence of the interventions on the relative reference projected frontal area, which implies that it is equally difficult to recapture the reference position in the first, second or third test. This study reports no training effects of vibrotactile feedback during the interventions since there is no improvement in recapturing the reference position when the no-feedback intervention test is performed after the vibrotactile feedback test compared to before the vibrotactile feedback experiment.

Practical Applications and Limitations

Further studies should clarify the effect of different levels of competitiveness (competitive or amateur cyclist) and different bike types (time trial bike or road bike) on the projected frontal area and on the use of vibrotactile feedback, since the sample size included in this study is insufficient to detect valuable differences.

In general, vibrotactile feedback can be used as an assisting function to find or maintain the reference cycling position for amateurs. It can be used as a reminder for the reference position for competitive riders, especially effective when fatigue increases at higher cycling intensities[26]. However, the most interesting application of vibrotactile feedback is in time trial training or races, where the aerodynamic drag is the dominant factor[10,11].

It is obvious that the absolute projected frontal area is higher for the road bike and that it is easier to recapture the reference cycling position using a time trial bike. The time trial bike and especially the handlebar is engineered to fix and maintain cyclists in their most aerodynamic position[15], which limits the movement of the torso and arms during cycling effort to optimize the cycling performance[27]. However, vibrotactile feedback also can have utility during road races in specific circumstances such as in a breakaway[15] or during sprints.

The main limitation is that the results of the indoor training bike system to correct the aerodynamic cycling position do not guarantee similar results in outdoor situations[28], where several factors such as focusing on the course, the influence of wind speed and direction and course topography should be considered[29]. Since it is impractical to completely simulate all outdoor effects in the indoor setup, future research must aim to develop an aerodynamic training system for outdoor situations, which can be obtained using applications to estimate outdoor aerodynamic drag[30,31] combined with vibrating elements to provide real-time feedback. Further studies should clarify the opportunities of vibrotactile feedback in outdoor cycling and the effect thereof on training and performance.

Conclusion

This study shows that it is difficult to recapture a predefined aerodynamic reference cycling position from wind tunnel experiments or projected frontal area calculation without any feedback. However, using vibrotactile feedback the participants can recapture an aerodynamic and ergonomic reference position significantly more accurately compared to no feedback. The calibrated aerodynamic reference position and the sensitivity of the vibrotactile feedback can be personalized to obtain an optimal training system for each cyclist. The presented method can assist and correct cyclists in recapturing their reference position, which can lead to optimized cycling performances.

Disclosure statement

The authors report no conflict of interest.

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Tables

Table 1: The 12-minute long protocol that participants had to follow for all three interventions. Capturing the reference position with the minimal projected frontal area was alternated with periods of one minute where participants were sitting upright and standing to investigate the accuracy of recapturing the reference position using the three interventions. The marked (*) sections indicate the reference periods where feedback was provided in case of vibrotactile feedback interventions.

Figure captions

Figure 1: The indoor training bike system. a) The test setup with the camera to calculate the projected frontal area and the smart trainer to adapt the power based on the projected frontal area calculations to provide realistic cycling situations and b) the training system with time trial bike installed on the smart trainer and participant with the vibrating element attached to the C7 to provide vibrotactile feedback on the aerodynamic cycling position.

Figure 2: The projected frontal area calculation. a) An image of the frontal view of the camera and b) the pixel recognition of the image to calculate the projected frontal area.

Figure 3: The different cycling positions during the protocol with a) the reference position with minimal projected frontal area, b) sitting upright and c) standing. After deviations in b) and c), participants had to recapture the reference position in a) using three interventions: one without feedback and two times with vibrotactile feedback with different margins of error.

Figure 4: The average relative reference projected frontal area for the 14 participants and the three interventions.