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Acute effect of foot orthotics on drag area and perceived comfort in cyclists affected by an anatomic asymmetry in time trial position

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Abstract: The aim of this study was to analyse the acute effect of foot orthotics on drag area (ACd) and perceived comfort in cyclists affected by a lower limb length inequality (LLLI) in time trial (TT) position. Twenty-nine well-trained cyclists performed two discontinuous incremental exercises (before and after orthopaedic correction) using their personal TT bicycle and equipment on a 250-m indoor velodrome. The ACd was unchanged in both the test group (TG) (0.5%, p = 0.707) and the control group (CG) (-1.4%, p = 0.276), whereas the perceived comfort was improved in the TG (+6.2%, p = 0.002) and stabilised in the CG (+0.7%, p = 0.546), after the fitting of the foot orthotics. Pelvis movements were decreased (small effect size) in the TG (-6.2%, p = 0.093, ES = 0.251), whereas they were increased (small effect size) in the CG (+5.2%, p = 0.159, ES = 0.215). TT position was slightly improved by compensating for a LLLI, as the ACd was stabilised and the level of comfort was improved. Thus, cyclists affected by a LLLI are recommended to compensate with foot orthotics in order to improve their level of comfort and consequently their performance in TT position.

Keywords: Pelvis Tilt, Foot Orthotics, Aerodynamic Drag, Time Trial, Cycling.

1. Introduction

The position of a cyclist on his bicycle and individual anthropometric parameters are very important factors to consider in order to optimise pedalling biomechanics (Bini, Hume, Croft, & Kilding, 2013; Burke & Pruitt, 2003; Silberman, Webner, Collina, & Shiple, 2005). Postural imbalances can lead to increased joint stress in the lower limbs. Therefore, different methods, such as chiropractic adjustment (Jarosz, 2010), kinesio taping (Hebert-Losier, Yin, Beaven, Tee, & Richards, 2019) or foot orthotics, can be used to reduce these joint stresses. Orthotics seem to be of interest to reduce unwanted movements such as pelvis tilt during the pedalling cycle and to restore the symmetry of the movements during both the pushing and pulling phases of the pedalling cycle. In the scientific literature, the studies that have analysed physiological parameters such as oxygen consumption (VO2) with and without foot orthotics have had conflicting results (Anderson & Sockler, 1990; Hice, Kendrick, Weeber, & Bray, 1985). Hice et al. (1985) observed a significant decrease in VO2 with foot orthotics when cyclists performed submaximal constant exercises in the laboratory. Conversely, the study by Anderson and Sockler (1990) reported that foot orthotics provided no significant difference in VO2. Yang (2013) showed that when riders cycled in the laboratory using a personal bicycle and working at two different intensities (125 W and 150 W), foot orthotics had beneficial effects on the muscular activity of the vastus medialis, vastus lateralis and gastrocnemius medialis, which are particularly stressed during the pushing phase. Activation time of those muscles decreased, which led to a decrease in muscular fatigue, while the peak output power increased. While previous studies (Hice et al., 1985; Yang, 2013) have shown the positive effects of foot orthotics on physiological and biomechanical parameters in the laboratory, a recent study by Bini et al. (2016) showed that asymmetry of the lower limbs did not influence performance during a 20 km time trial (TT) on a cycle trainer in the laboratory. However, those authors did not focus in detail on the three following key factors of TT position: aerodynamics, mechanical power (PO) and comfort (Burt, 2014). To the best of our knowledge, no study has yet reported the effect of foot orthotics on drag area (ACd) and comfort in TT position in well-trained cyclists.

Computational fluid dynamics (CFD) has shown that the bicycle contributes ~20% of the ACd, while the cyclist contributes ~80% (M. D. Griffith et al., 2014). Looking more closely at the contribution of the cyclist in TT position, the legs, head and arms are the most important elements for the ACd, contributing 53%, 19% and 14%, respectively (Defraeye, Blocken, Koninckx, Hespel, & Carmeliet, 2011). As for the legs, it is important to note that the aerodynamic resistance varies (~20%) depending on the position of the cranks, and therefore of the legs, during the pedalling cycle (Crouch, Burton, Brown, Thompson, & Sheridan, 2014; Crouch, Burton, Thompson, Brown, & Sheridan, 2016; M. D. Griffith et al., 2014). This fluctuation of the ACd is mainly due to the drag coefficient (Cd), since the frontal area (A) varies by only 2% during a pedalling cycle. Over 60% of the variation in ACd with leg position can be explained by the large change in the pressure distribution on the back and hips throughout the crank cycle. These findings have also been supported by recent studies that include the dynamic motion of the legs using a realistic pedalling cadence (Crouch, Burton, LaBry, & Blair, 2017; Crouch et al., 2016; Crouch, Burton, Thompson, et al., 2014; Martin D. Griffith et al., 2019). Considering that a lower limb length inequality (LLLI) induces a pelvis tilt (Kwon, Song, Baek, & Lee, 2015), it is legitimate to hypothesise that the air flow could be disturbed by this leg length discrepancy, which would then increase the Cd.

Although the pursuit position is very aerodynamic, most well-trained cyclists cannot sustain this position much beyond the duration of the event and need the comfort factor to be taken into consideration (Burt, 2014). This is partly due to the fact that it is not possible to be as powerful and aerodynamic for a 40-minute TT as for a 4-minute TT. If the TT position is not relatively sustainable, all the benefits will be lost because the rider will shift position before settling back down again. Of course, holding such an extreme position for a long time can also cause physical damage. Thus, for longer TTs, a modicum of comfort is important for optimal performance. Millour et al. (2016) measured an increase in perceived comfort with foot orthotics in a seated position, but no study has yet reported the effect of foot orthotics on perceived comfort in TT position.

The aim of this study was to analyse the acute effect of foot orthotics on ACd and perceived comfort in TT position in well-trained cyclists affected by a LLLI. It has been hypothesised that for a given PO, foot orthotics would induce a slight decrease in ACd and improvement in perceived comfort, since LLLI may affect the biomechanics of the cyclist.

2. Methods

Participants

Twenty-nine well-trained cyclists (De Pauw et al., 2013) volunteered to participate in the study after being informed of the aims and procedures. All subjects were licensed to the French Cycling Federation. Subjects were assigned to two groups, a test group (TG; n = 16) and a control group (CG; n = 13) based on their degree of anatomical asymmetry. All subjects were regularly selected for French cycling teams and were TT specialists. Their mean ± standard deviation values for age, height and body mass were 19.5 ± 2.0 years, 174.0 ± 8.3 cm, and 67.0 ± 9.1 kg, respectively, for TG and 19.8 ± 3.3 years, 175.1 ± 9.7 cm, and 66.9 ± 7.4 kg for CG. No significant difference was observed between the two groups in the previous data. The riders followed a regular training regimen and participated in races throughout the season. Prior to testing and after having received a full explanation of the nature and purpose of the study, each cyclist provided written informed consent. The study was approved by the local ethics committee of the University and conducted in accordance with the ethical standards outlined by Harriss and Atkinson (2011).

Experimental design

The cyclists performed two discontinuous incremental exercises (before and after orthopaedic correction) using their personal TT bicycles and equipment (e.g., helmet and skinsuit) on a 250-m indoor velodrome (Saint Quentin en Yvelines, France). The two testing sessions were separated by one hour for each cyclist and performed with the same equipment. Cadence was recorded throughout the two testing sessions with a Powertap G3 hub (Powertap, Madison, USA) located at the rear wheel (Bouillod, Pinot, Soto-Romero, Bertucci, & Grappe, 2017). The pedalling cadence was free during the first session, and cyclists were asked to reproduce the same pedalling cadence during the second session by using the same gear on each incremental step. The bicycle tire pressure was inflated to 800 kPa.

All subjects were examined by an experienced podiatrist between the two testing sessions to diagnose a LLLI using current clinical assessments (Brady, Dean, Skinner, & Gross, 2003). First, a clinical exam on the table was performed to identify LLLI greater than 5 millimetres with a palpation meter (Petrone et al., 2003). Second, the diagnosis of LLLI found on the table was compared in standing position to evaluate the pelvis tilt induced by the LLLI on the same side and to exclude all other diagnoses (Bassani et al., 2019). Third, a cycling clinical control was done to validate the pelvis tilt on the saddle when pedalling using a home trainer (Hammer Direct Drive Trainer, CycleOps, Madison, USA). The cyclists without pelvis tilt were included in the CG and received no change for the second testing session. The cyclists for which a pelvis tilt was validated were included in the TG and received custom foot orthotics moulded under the feet with medial arch support and a 3 millimetre spacer under the shoes on the side of the shorter limb. The cyclists were aware of these changes and performed the second discontinuous incremental exercises after a very short adaptation period. Indeed, the cyclists were required to pedal a few minutes on the velodrome in order to acclimate to the new supports and to confirm that the podiatrist did not make an error.

Measurement of ACd

The cyclists performed two discontinuous incremental exercises on the velodrome at speeds (V) from 30 km·h-1 to 50 km·h-1, increasing their V by 2 km·h-1 every 90 seconds. Resistive force (RT) was determined from the measurement of PO at constant V on each incremental step as follows: RT = PO·V-1. RT was then plotted against V2 to obtain the RT-V2 linear regression (Grappe, Candau, Belli, & Rouillon, 1997). The equation of the linear regression to determine ACd was RT = ◎V2 + ◎, where ◎ = ACd "· 0.5 · ϱ" and ϱ (kg·m-3) is the air density, which was measured with a weather station (Kestrel 4250 Racing Weather Tracker, KestrelMeters, Minneapolis, USA). PO and V were measured throughout the two testing sessions with a Powertap G3 hub located at the rear wheel (Bouillod et al., 2017) using a frequency of 1 Hz and were recorded in a Garmin power control (Garmin 810, Olathe, USA). To ensure that accurate measurements were acquired by the Powertap power meter, the zero-offset frequency was adjusted before each session according to the manufacturer's instructions. The data were analysed with the TrainingPeaks software (WKO4, Peaksware, Boulder, USA). A beeper was used as external reference of the bicycle V to manage the pace and to allow the

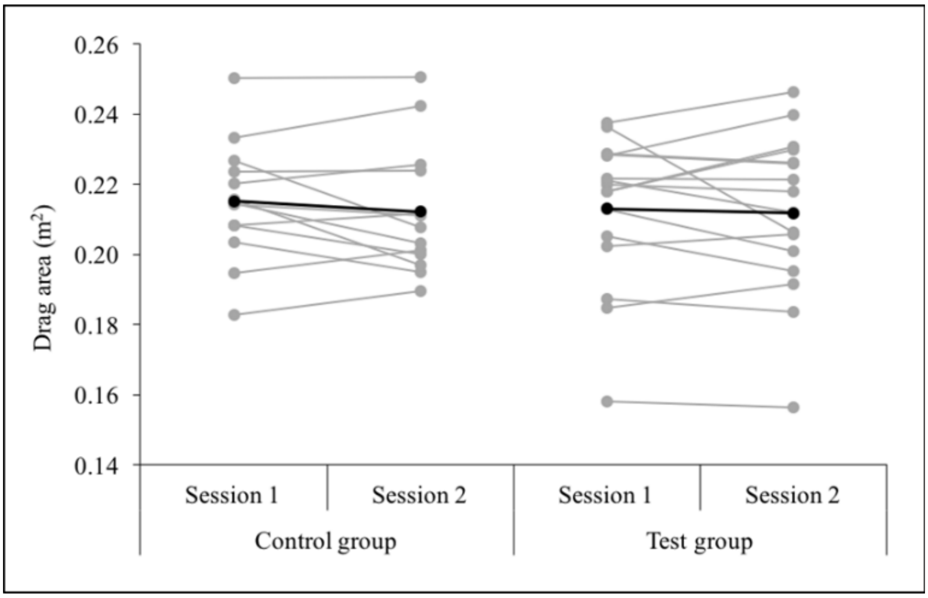

Figure 1. Scatterplot representing the acute effect of foot orthotics on drag area. Grey lines: individual values; black lines: mean values.

rider to keep the same position during the entire exercise.

Measurement of perceived comfort

A visual analogue scale from 0 (very uncomfortable) to 10 (very comfortable) was used to assess the comfort (Price, McGrath, Rafii, & Buckingham, 1983) of fourteen different anatomical locations at the end of each session: left and right feet, left and right lower limbs, saddle, back, head, left and right upper limbs, left and right elbows, left and right hands and general comfort. All these data were averaged to obtain a unique comfort rating.

Measurement of pelvis movements

The cyclists were equipped with a wireless system based on an iNEMO Inertial Measurement Unit (IMU, ST Microelectronics, Geneva, Switzerland) located at the pelvis level. The pelvis movements were quantified by measuring the angle variation (in degrees) around the Y-axis, which represented the longitudinal anatomical axis. Data were measured at a frequency of 50 Hz.

Statistical analysis

Descriptive statistics were calculated, and all data were expressed as mean ± standard deviation. Statistical analyses were performed using SigmaPlot 12.0 software (Systat Inc. San Jose, USA). The Kolmogorov-Smirnov-Lilliefors test was used to verify Gaussian distributions; all data were normally distributed. The data were analysed with a paired t-test. Effect size (ES, Cohen's d), which represents the ratio of the mean difference over the pooled variance, was used to estimate the magnitude of the difference. The difference was considered trivial when ES ≤ 0.2, small when ES ≤ 0.5, moderate when ES ≤ 0.8, and large when ES > 0.8. The coefficient of variation (CV) was computed under the different testing sessions considered herein. A linear regression was performed to determine whether the pelvis movements could predict perceived comfort. The statistical significance was set at $p < 0.05$.

3. Results

Figure 1 shows that the ACd did not change significantly in either the TG (-0.5%, p = 0.707, ES = 0.054 and CV = 2.6%) or the CG (-1.4%, p = 0.276, ES = 0.17 and CV = 2.6%) after the fitting of the foot orthotics. Among the sixteen cyclists included in the TG, ten exhibited reduced ACd after receiving an orthopaedic correction, whereas the other six showed increased ACd.

The pedalling cadence was also unchanged between the two sessions in both the TG (-0.3%, p = 0.847, ES = 0.051 and CV = 3.7%) and the CG (+1.4%, p = 0.467, ES = 0.179 and CV = 2.4%).

Pelvis movements were decreased (small ES) in the TG (-6.2%, p = 0.093, ES = 0.251 and CV = 7.8%), whereas they were increased (small ES) in

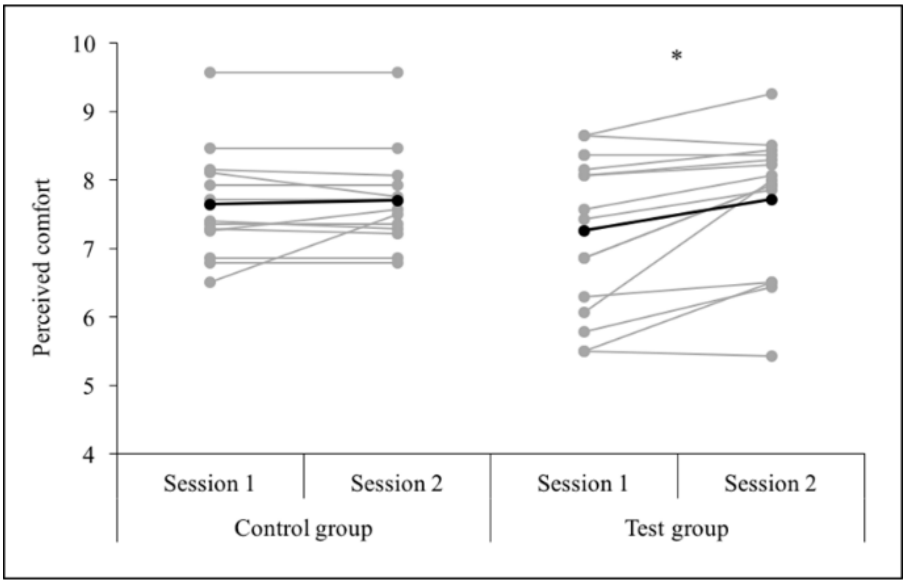

Figure 2. Scatterplot representing the acute effect of foot orthotics on perceived comfort. Grey lines: individual values; black lines: mean values.

the CG (+5.2%, p = 0.159, ES = 0.215 and CV = 6.6%).

Figure 2 shows that perceived comfort was improved in the TG (+6.2%, p = 0.002, ES = 0.432 and CV = 5.5%) and stabilised in the CG (+0.7%, p = 0.546, ES = 0.074 and CV = 1.4%) after the fitting of the foot orthotics. Fourteen cyclists increased their comfort level after receiving an orthopaedic correction, whereas the other two slightly decreased their comfort level.

* Significant difference between the two testing sessions ($p < 0.05$).

Finally, perceived comfort was correlated with pelvis movements ($r = -0.46$, $p < 0.05$). The lower were the pelvis movements, the higher was the comfort.

4. Discussion

The main findings of this study were that ACd was not significantly affected by orthopaedic correction compensating a LLLI, whereas perceived comfort was improved with foot orthotics via a decrease in the pelvis movements. Only the result concerning the comfort improvement was in accordance with our main hypothesis. The results suggest that the TT position of the well-trained cyclists should be more performant, since the ACd was stable and the comfort increased over the course of the velodrome testing sessions. The improvement in comfort was not negligible, since this element constitutes one of the three key factors of cycling performance (Burt, 2014).

The similar ACd measured before and after orthopaedic correction demonstrate that the aerodynamic component of the TT position was not improved by slightly modifying the support on the pedals. Several elements could explain the fact that the ACd was not significantly different between the two testing sessions in both groups. First, the effect of immediately fitting foot orthotics was tested without a certain duration of training. Studies in the literature are controversial concerning the time needed to adapt to foot orthotics. Earlier work has indeed shown that foot orthotics elicit immediate/short-term effects on lower limb muscle activity during walking (Tomaro & Burdett, 1993) and running (Nawoczenski & Ludewig, 1999). In contrast, one study reported that a medium-term adaptation (from 1 to 6 months) (Hsieh & Lee, 2014) was needed to induce a modification of the pedalling pattern by neuromuscular adaptation. It would be interesting to assess our well-trained cyclists after a medium term adaptation period to investigate the effect of foot orthotics on ACd and comfort after a longer period. However, it is unclear if the effects provided by the foot orthotics would be different following a longer adaptation period (Bonacci, Chapman, Blanch, & Vicenzino, 2009; Macdermid & Mann, 2015; Yeo & Bonanno, 2014).

In addition, changes in muscle activity and lower limb kinematics showed high inter subject variability in a previous study of the individual responses to foot orthotics (O'Neill, Graham, Moresi, Perry, & Kuah, 2011). Our results also highlight these individual responses to foot orthotics in ACd. Therefore, an individualised approach is recommended in cycling orthotic prescriptions. Although foot orthotics did not influence the immediate/short-term kinematics of the lower limbs in previous studies, it would seem that the ankle is a key element in the pedalling cycle. Differences in range of motion between right and left pattern (Macdermid & Mann, 2015; Rodano, Squadrone, & Castagna, 2009) could compensate the leg length discrepancy and decrease pelvis tilt during each pedal stroke. Considering that the kinematics of the lower limbs were not measured in our study, it is not possible to speculate further.

Although ACd was not affected by foot orthotics, our results showed that pelvis movements around the longitudinal anatomical-axis were decreased (small ES) in the TG (-6.2%), whereas they were increased (small ES) in the CG (+5.2%) for a given V. This suggests that a reduction in LLLI tends to decrease the pelvis movements. It would be interesting to measure gas exchange in a future study in order to analyse whether this reduction in pelvis movements could decrease the energy cost (oxygen uptake for a given V). Additionally, our results highlight a significant relationship between pelvis movements and perceived comfort. Lower pelvis movements were related to higher comfort.

The increase in comfort with foot orthotics was in accordance with the preliminary study of Millour et al. (2016), who observed a larger increase in comfort (+39%). The comfort represents one of the three key factors of cycling performance even if it does not directly influence TT performance, which is determined by the ratio of PO to ACd (Bouillod et al., 2016; Peterman, Lim, Ignatz, Edwards, & Byrnes, 2015). Indeed, the contribution of comfort in TT performance resides in the ability of the cyclist to sustain his TT position, and consequently the highest PO/ACd ratio, over time. Since our results show that an increase in comfort with foot orthotics has no effect on ACd, it is reasonable to suggest that this improvement in comfort could increase the PO and/or the holding time of PO for a given position on the bicycle. Thus, it would be interesting to investigate the effect of foot orthotics on PO in a future study.

It is important to note some limitations of the present study. The reproducibility of the cyclist position could explain the similar ACd measured before and after orthopaedic correction. A mean CV of 2.6% (range from 0.1% to 6.5%) was reported in the CG. Although the reproducibility was considered as good as that in the study of Grappe et al. (1997) (CV = 3.2%), a CV of 2.6% could be still too high to detect a significant effect of foot orthotics on ACd. Additionally, the method of linear regression reaches the limit of sensitivity of the measurement to evaluate small changes in ACd (Garcia-Lopez, Ogueta-Alday, Larrazabal, & Rodriguez-Marroyo, 2014), and this could also explain the similar ACd measured before and after orthopaedic correction. Concerning pelvis tilt, it is important to note that the testing sessions were performed in a velodrome, which could influence our results due to the slope in the straightaways (10 15°) and in the curves (40-45°). By tilting the pelvis to the right, the well-trained cyclists would compensate for the gravitational force in both the straightaways and the curves and for the centrifugal force in the curves.

5. Practical Applications.

This study shows that the ACd was not significantly affected by an orthopaedic correction compensating for a LLLI, whereas the perceived comfort was slightly improved with foot orthotics. This increase in comfort with foot orthotics was induced by a decrease in pelvis movements, considering the negative relationship between these two parameters. The results suggest that the TT position of the well-trained cyclists was slightly improved, since the ACd was stabilised and the comfort improved. This increase in comfort is not negligible, since this element constitutes one of the three key factors of cycling performance. It could improve the ability of the cyclist to sustain the highest

PO/ACd ratio over time. Finally, well-trained cyclists affected by a LLLI can compensate with individualised foot orthotics in order to improve their comfort and consequently their TT performance.

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7. Conflict of interest

The authors report no conflict of interest

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