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Exploring the effects of trunk acceleration on saddle position and the drag coefficient

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ABSTRACT

Triathletes often use a time trial bicycle with an increased seat tube angle combined with aerodynamic handlebars that allow for a decreased upper body and trunk to improve aerodynamics. In this respect, the adjustment of the seat tube and saddle is an important feature of fitting bicycle to triathlete to positively impact performance. Limited published evidence concerning trunk acceleration, saddle position and aerodynamics by way of the drag coefficient (*Cd*) in triathlon cycling makes comparisons difficult. Therefore, an overground varied cycle cadence in a previously validated saddle position was conducted to detect differences in trunk acceleration magnitude whilst a multivariable linear regression was used to estimate *Cd* based on saddle position, trunk acceleration and cadence. Data was collected by a trunk-mounted triaxial accelerometer to estimate kinematic determinants of triathlete cycling performance in conjunction with trunk acceleration magnitude and cadence that contribute to *Cd.* Seven participants completed a 1 x 5 km overground cycling trial at varied cadence on a characteristic triathlon circuit. Multiple linear regression was used to estimate that cycling at higher cadences increased trunk acceleration magnitude with a projected *Cd* of 0.277. Longitudinal trunk acceleration represented 39% of the outcome variable explained by the model. To illustrate the practical relevance of the statistical models, mean total trunk acceleration and cadence were applied to predict *Cd*. Higher magnitudes of total trunk acceleration combined with cycling at a cadence of 95-100 rev/min^1 resulted in greater *Cd* (0.283).

Keywords: Accelerometer; Trunk; Drag; Regression; Cycling.

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INTRODUCTION

The relationship between bicycle and triathlete is significant given the need to maintain effectiveness without causing undue fatigue as to compromise cycling efficiency. Measuring and understanding the biomechanical properties of this system in overground settings is an important and ongoing challenge for sport scientists and coaches interested in cycling performance. Upper and lower body position is critical to dictate muscle activation (Bini, Hume, & Croft, 2014) with changes in upper body lean and saddle height referred as the two most important settings during pedalling (Ricard et al., 2006; Hamley & Thomas, 1967). These combined changes can effect crank motion given that it is commonly contained by the angular path of the crank that elicits a combination of linear and angular motion to the lower limbs. A change in body position resulting from alterations to saddle position will effect knee angle (Bini, Hume, & Croft, 2014) and pedalling cadence (Heil et al., 1997) as well as aerodynamic drag. In the laboratory, where resistive forces are controlled or minimised, these factors have been successfully used to predict simulated time trial performance (Coyle et al., 1985). When cycling outside on level terrain the total resistance impeding the forward motion of a bicycle-triathlete system is determined by aerodynamic resistance. This indicates that the bicycle-triathlete system needs to be individually tailored. Firstly, anthropometric characteristics are variable due to differences in body size and proportions. Secondly, motivations for cycling have important effects on riding position. For instance, a triathlete is likely to select a position that minimises aerodynamic drag and sacrifices comfort.

Trunk position has been identified as an important parameter that can effect cycling performance and aerodynamic resistance. For example, upper body position has been related to changes in activation of lower limb muscles (Hamley & Thomas, 1967), later shown to effect cycling performance (Price & Donne, 1997). Notably, greater trunk flexion was found in triathletes (Bini, Hume, & Croft, 2014) due to the need for reducing frontal projected area (Dorel, Couturier, & Hug, 2009) relative to reducing the drag coefficient (*Cd*) with detrimental effects in pedal pulling forces (Bini et al., 2013). In this regard triathletes use aerodynamic bars to reduce their projected frontal area and improve aerodynamics. Given triathletes seek minimum drag resistance when cycling, trunk position is critical to achieve optimal performance (Hodges, Cresswell, & Thorstensoon, 1999).

The greatest potential for improvement in cycling speed is in aerodynamics (Faria, Parker, & Faria, 2005) as when cycling on level ground at speeds greater than 14 m/s, aerodynamic drag is the most important resistive force (Debraux et al., 2011). Nevertheless, measuring aerodynamic resistance force during cycling can be complex. Direct measures include wind-tunnel tests (Kyle, 1991) and motorised towing (Capelli et al., 1993). Even though these direct measurements are accurate, they are impractical for most researchers and practitioners. Since measuring aerodynamic resistance can be complex, it is sometimes assumed to be directly proportional to measures or estimates of the projected frontal area (PFA) of the bicycle and rider (Olds & Olive, 1999). This assumes, though, that between individuals, aerodynamic resistance changes predictably with changes in projected frontal area. However, evidence exists to the contrary. Previous research shows a lack of proportionality between an individual's measured frontal area and aerodynamic resistance. As noted by Debraux et al. (2011), this discrepancy must be due to variability in the coefficient of drag (*Cd*) which is influenced by the shape of the bicycle and rider which does not change proportionally with changes in projected frontal area (*Cd*A*). As triathlon bicycles differ from traditional road bicycles and anthropometrics differ amongst individuals and genders, there is a need for additional research into both alternate methods to assess *Cd* in overground settings.

Recently, it has been demonstrated that measuring mechanical power output and speed overground with cycle mounted power meters is a viable and accessible technique for determining aerodynamic and rolling resistance (Martin et al., 2006; Debraux et al., 2011). This technique, in combination with standard biomechanical profiling, could improve our ability to predict field performance since it has been argued that physical factors resisting forward motion play a larger role in performance outcome than physiological variables (Jeukendrup & Martin, 2001). Accordingly, the purpose of this preliminary study was to quantify kinematic determinants of triathlete cycling performance with linear trunk acceleration magnitude and cadence that contribute to *Cd* during cycling. Correlations between cadence and trunk acceleration magnitudes using a triaxial accelerometer were then equated against estimated *Cd*. We hypothesised that a triathlete's average trunk acceleration would not predict level *Cd* time unless normalised to some representation of combined cadence and trunk acceleration.

METHODS

Seven well-trained recreational triathletes (age: 42 ± 11 yrs., height: 170 ± 6 cm, weight: 68 ± 6 kg, weekly training frequency 7 ± 1 hrs, volunteered to participate in this preliminary study. After explanation of experimental procedures, possible risks and benefits, each triathlete provided written informed consent. Triathletes were recruited from local triathlon clubs and all had a minimum of one-year experience competing at a recreational level in sprint distance triathlon (750 m swim, 20 km cycle, 5 km run). Ethical approval was granted by Charles Darwin University Ethics committee (HREC 030317). Triathletes also completed a PAR-Q + health screening questionnaire prior to taking part. All participants were healthy and had no known neuromuscular or musculoskeletal conditions at the time of the study. Participants were asked to preserve their habitual diet for the study but refrain from intense exercise in the 24 hours prior to testing. Participants were evaluated at the same time of the day, between 06:00 – 09:00. These specific times were knowingly selected due to the overground circuit being free from interference (i.e., vehicles). Triathletes performed a 5 km overground varied cadence cycle protocol on an overground circuit (Table 1). Standard bicycle settings included wheel circumference 2096 mm, chainring 52 ± 0.2 (ratio 5:10), and trye size (23 mm with 700 mm outer diameter). Other mean bicycle settings were: saddle height: 78 ± 0.4 cm, inseam: 75 ± 4 cm, seat tube angle (STA): 78° ± 0.49).

Table 1. Varied cadence protocol used.

Epoch (minutes)	**Warm up^1**	**0-3 min^1**	**3–6 min^1**	**6–9 min^1**
Cadence condition	SSC*	55-60 rev/min^1	75-80 rev/min^1	95-100 rev/min^1

** SSC = self-selected cadence; Not included in overall time.*

The initial three minutes was performed at self-selected pace and served as a warm up in order that partcipants were familiarised with the testing protocols. This duration was not recorded. Cadence was measured in the revolutions per minute unit (rev/min^1). with cadence conditions based on a previously established protocol (Chapman et al., 2007). Cadence was monitored with fitted cadenec meters that were displayed on participant bicycles. Changes to cadence were verbally communicated to participants. To signify the completion of one cadence condition, the sensor was manually synchronised by the authors in order to detect synchronisation points in the raw data during post hoc analysis. The testing order was the same for all participants with no additional instructions provided. Triathletes cycled in an aerodynamic position, defined as elbows on the pads of the aero-handlebars with elbow angle close to 90° and the upper portion of the trunk parallel to the ground.

The 5 km cycle protocol was performed on a predominately flat circuit (average gradient 0%) that is regularly used by triathletes for time trial (TT) performance. The circuit was purposely selected to avoid increased braking performance, as is common in triathlon and TT performance. This layout allowed participants to cycle continuously with no stop signs or traffic lights impeding their effort. As the circuit was commonly used in training and elite performance contexts, it therefore permitted for appropriate evaluation of the sensor relative to real-life performance application. In this sense, triathletes were able to adopt their familiar aerodynamic position. This position increases reliance on using the integrated gear shifters located at the end of the aerodynamic bars, which differs from that used by road cyclists.

Standardised saddle position

Prior to performing the warmup, measurements of inseam leg length were recorded using a standard tape measure in order to determine participant anthropometrics and adjust saddle height to limit variability. Inseam measurements were then taken and applied to an equation (Ferrer-Roca et al., 2012) to adjust saddle position with clipless pedals (i.e., 108.6–110.4% of inseam). (Equation 1).

$$SH = 22.1 + (0.896E) - (0.15KA) \qquad (1)$$

Where SH is saddle height (cm), *E* is inseam length (cm), and *KA* is the recommended knee angle (30–40°).

To ensure validity, measurements of knee flexion angle were recorded by the researchers using a goniometer with participants in a static, aerodynamic position. Knee flexion was measured with the pedal placed at the bottom dead centre on the right side of the triathlete at the greater trochanter and lateral femoral condyle. Saddle position was manually adjusted according to Equation 1 before participants assumed their natural aerodynamic position. Aside from saddle position, participants did not have bicycle configuration standardised as this would have affected muscle recruitment patterns (Bini & Hume, 2016). Northwave tri-sonic cycling shoes (Northwave, Via Levada, Pederobba TV, Italy) with Shimano SPD-SL pedals with yellow cleats with a tolerance of approximately 6° flotation and tension were used by all participants. To standardise foot placement, the head of the first metatarsal was positioned directly above the pedal spindle with the foot placed laterally in the middle of the pedal (Korff & Jensen, 2007). Tight-fitting synthetic clothing was worn by all participants.

During measurement, a single tri-axial accelerometer (SABELSense. 52 mm x 30 mm x 12 mm, mass 23 g; resolution 16-bit, full-scale range 16 *g*, sampling at 100 Hz: SABEL Labs, Darwin, Australia) was fixed to participants' spinous process (L5/S1) using double sided elastic adhesive tape (Medtronic Australasia Pty Ltd, Macquarie, NSW). Specifically, linear accelerations at the sensor were measured on the skin over spinous processes, defined as the lumbar vertebrae position 5 (L5) and sacrum vertebrae position 1 (S1). The basis for this location is that it is the unique and closest external point to trunk movements and the point of distribution of the weighted position vectors that sum to zero. During cycling, lower limb movement in the sagittal plane was constrained to a circular path by the geometry of the bicycle (i.e., by crank length and pedals). Within these constraints the cyclist can vary pedalling technique by changing temporal kinematics of their lower limbs and this change can be detected by the accelerometer. Consequently, if a triathlete has unwanted body movement, (i.e., excessive mediolateral movement when the direction of travel is linear) the acceleration of that movement can be detected by the sensor.

Prior to commencement, a static calibration was performed (Lai et al., 2004). This also served also to check channel orientations aligned to each axis of interest (Lee, Wheeler, & James, 2019). The device hardware specifications included a ± 2 *g*, ± 4 *g*, ± 8 *g*, ± 16 *g* selectable scale. The sensor was positioned to measure linear trunk acceleration data in three orthogonal planes where longitudinal (LN), mediolateral (ML) and anteroposterior (AP) aligned with X, Y and Z respectively (Figure 1).

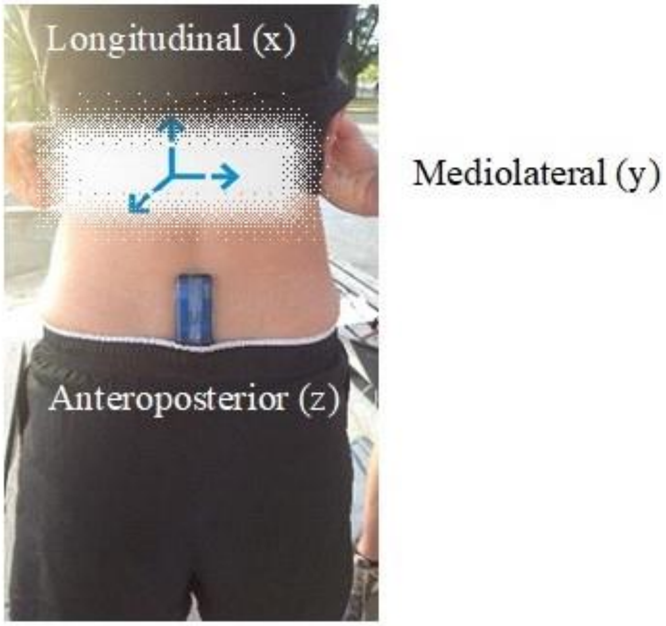

Figure 1. Representation of orthogonal axes orientation and sensor used in study.

No filtering was applied to the sensor data. As the trunk undergoes movement the magnitude of trunk acceleration, as observed at the spinous process, will be a function of its local X, Y, and Z acceleration components. In this respect a postural alteration will be apparent in the local acceleration components. In this paper, trunk accelerations of each local component were compared to examine the longitudinal, mediolateral and anteroposterior changes with a homogeneous method applied to compare trunk acceleration magnitudes. Accelerations were assessed by analysing each 3-minute (epoch) cadence condition, excluding the initial warm up period. Therefore, due to this methodology, any excess braking or cornering that may have caused significant acceleration spikes would have been reduced. The authors considered this as a '*settling period*'. This process also accounts for the negligible braking or sudden cornering. The mean trunk accelerations were then calculated. Means and standard deviation were subsequently reported for the local X, Y and Z acceleration components. Longitudinal acceleration was used to detect a change in posture and was identified where the acceleration magnitude began increasing towards its largest peak. Data was recorded continuously throughout testing before being transferred to a computer for analysis.

The Drag Coefficient

The *Cd* is a dimensionless quantity and is largely determined by the shape and smoothness of the bicycle and rider (Brancazio, 1984). By manipulating the contours of a surface to produce a more streamlined aerodynamic efficient shape, the *Cd* can be reduced. Estimates of the *Cd* have been reported for a range of bodies. Capelli et al. (1993) reported a projected *Cd* of 0.645 for aerodynamic bicycle frames while Olds et al. (1995) projected value of 0.592. In contrast, Garcia-Lopez reported values of 0.296–0.341 from wind tunnel testing of cyclist position. However, as the velocity was 15 m/s (54 km/h) this does not necessarily reflect capability of recreational athletes given the power needed to overcome drag forces.

To consider the various interrelated variables that effect *Cd*, a series of calculations were applied based on participant measurements (height cm, mass kg, inseam leg measurement cm) and assumed (independent) variables including mass of bicycle and accessories, fluid density at sea level (standard sea level) equal to $\rho = 1.225$ kg/m³, appreciable wind speed (8 km/h), and speed based on average cadence. The effect of gravitational acceleration (*g*) was equal to 9.80655 m/s². Measurements for front and rear wheel tires were classified as a high-pressure narrow racing tire with an average 700 kPa with the experiment performed during ambient conditions (16-17° C, 60–65% relative humidity). To estimate projected frontal area (FA), the method used by Bassett et al. (1999) was applied. This method utilised the cyclist's height and weight to estimate the total FA in terms of height and mass while in the aero-racing position utilising aero bars (Equation 2).

$$FA = 0.0293H^{0.725} M^{0.425} + 0.0604 \qquad (2)$$

Where: FA = frontal area in m2; H = height in m; M = mass in kg.

Ignoring the other resistances for the moment, the power needed to overcome the aerodynamic drag commonly considers FA, air density, and speed. Though, as cadence was used in the current study, a method that incorporates bicycle roll-out was applied to substitute power for cadence in order to approximate speed. Firstly, bicycle roll-out (metres of development) was approximated by multiplying the bicycle gear ratio by the circumference of the wheel. This value represents the distance the bicycle will travel with one complete revolution of the crank. Triathletes in our study used a 52 chainring paired with a 10T cog which yielded the ratio 5:2. Thus, one complete rotation of the crank will cause the rear wheel to rotate 5.2 times with a rollout of 10.89 m. A standard 700 mm tyre rim (outer diameter) by 23 mm was used. The expected speed was therefore calculated according to Equation 3.

$$v = \left(\frac{R_{o1}}{1000}\right) x\ Cn\ x\ 60 \qquad (3)$$

Where v is speed in km/h¹, R_{O1} is roll-out ring size of 52 and cog size 10 x 2.096 circumference with *Cn* being cadence in rev/min¹.

Secondly, to finalise estimates of *Cd*, as bicycle drivetrains (with derailleur gears) can have efficiencies up to 98%, the chain lubrication, bearings and the gears can affect drivetrain efficiently significantly. To account for probable mechanical losses, drivetrain efficiency was set at 97.5% with the coefficient of rolling resistance (C_{rr}) standardised based on the aforementioned tyre selection on asphalt with the resultant value of C_{rr} 0.3218. Once approximations of *Cd* were obtained, the next step was to scale the raw sensor data into acceleration (m/s²) per cadence condition, as is common in sport science literature (James, 2006; Callaway et al., 2009). This allowed for acceleration magnitudes of the trunk in cumulative 5 km cycling. The final step was to build the regression model using triaxial trunk acceleration magnitude, cadence, and the estimated *Cd*.

Statistical analysis

The Gaussian distribution and sphericity were initially verified by the Kolmogorov-Smirnov test with a logarithm transform applied to decrease non-uniform data distribution. A two-way ANOVA was used to test the interrelationship of cadence and trunk acceleration magnitude on saddle position with the null hypothesis (H0) being that there is no difference to trunk acceleration magnitude between cadence and saddle position with equality between means. Multiple linear regression (MLR) was used as a statistical technique to envisage the outcome of *Cd*. In all analyses the statistical significance was set at 5% ($p < .05$) and final predictive models were accepted only if power and effect size (ES) were > 0.80. The ES, expressed as the Pearson's correlation coefficient, was interpreted as small ($r < 0.20$), moderate ($0.21 > r < 0.79$) and large ($r > 0.80$) (Cohen, 1988).

RESULTS

Based on Equation 2, FA was estimated to be 3.74 ± 0.45. The projected frontal area values calculated are similar to the weighing photograph and new method stated by Debraux et al. (2009) (i.e., 0.341 and 0.338 in an aerodynamic position). Triathletes completed the overground 5 km cycling protocol in 9.56 minutes (± 3.4). The cumulative mean for acceleration magnitude of the trunk was 4.55 (± 0.74) with mean cadence across the 5 km 77.09 rev/min^{1} (± 16.9). Trunk acceleration was significantly different when cycling at lower cadences. Despite large effect sizes, total trunk acceleration was not significant at the remaining cadences (Table 2).

Table 2. Adjusted saddle position against mean cadence.

Epoch	Mean cadence (rev/min^{1}) ± SD	Estimated speed (km/h)	Trunk acceleration	*p*	Effect size	Effect size magnitude inference
0–3 min^{1}	56.3 ± 1.49	17.57	Total acceleration (x, y, z)	.0014*	0.2	Moderate
3–6 min^{1}	77.00 ± 2.16	23.7	Total acceleration (x, y, z)	< .05	>0.8	Large
6–9 min^{1}	95.93 ± 2.12	29.93	Total acceleration (x, y, z)	< .05	>0.8	Large

** significant at < .05.*

Intra directional differences (between acceleration axis) were found between cadences for longitudinal trunk acceleration in two conditions. Difference in anteroposterior trunk acceleration was significant in the highest cadence ranges only. The multivariable regression model used trunk acceleration magnitude and cadence taken together with previously estimated *Cd*. Analysis based on axial directions and cadence condition was then stratified into 3-minute epochs in order to attain the separate effect of terms. Table 3 shows that as cadence increased to 75-80 rev/min^{1} and 95-100 rev/min^{1} so did the predicted *Cd*. With respect to individual directions of acceleration magnitude, both mediolateral and anteroposterior trunk accelerations were significantly higher than the lower cadences of 55-60 rev/min^{1} ($p < .001$). Estimated drag values were significantly higher in the peak cadence of 95-100 rev/min^{1} compared to the lower cadence range.

Table 3. Performance difference of trunk acceleration and cadence and estimation of *Cd*.

Epoch	Mean cadence (rev/min^{1}) ± SD	Effect of Terms: Acceleration	*p*	***Estimated Cd***
3–6 min^{1}	56.3 ± 1.49	Longitudinal Acc	.044*	0.272
		Mediolateral Acc	.141	
		Anteroposterior Acc	.264	
6–9 min^{1}	77.00 ± 2.16	Longitudinal Acc	.806	0.277
		Mediolateral Acc	.0104*	
		Anteroposterior Acc	< .0001*	
9–12 min^{1}	95.93 ± 2.12	Longitudinal Acc	.5717	0.283
		Mediolateral Acc	.0104*	
		Anteroposterior Acc	< .0001*	

** significant at p < .0001.*

When using variables without allometric scaling, the *Cd* was predicted to be 0.278 (± 0.014) based on the cumulative trunk acceleration in 5 km cycling. When the cumulative mean for tri axial acceleration was expressed along with mean cadence and mean *Cd*, the predictive model obtained produced a mean absolute percentage error (MAPE) of 3.6%. Correlations between *Cd* were observed between longitudinal acceleration ($r = 0.39$) (Figure 2) with an inverse relationship detected among anteroposterior trunk acceleration and *Cd* ($r = -0.33$). Apart from the correlations between accelerometric variables, the correlations between trunk acceleration and cadence *Cd* were notable. The relationship between total trunk acceleration in x, y, z, cadence and mean *Cd* was $r = 0.289$ (minima *Cd* 0.257~0.299 maxima *Cd*). The resultant equation (4) was:

$$Cd = 0.085 + 0.039 \cdot \text{Longitudinal Acc} - 0.00578 \cdot \text{Mediolateral Acc} - 0.000712 \cdot \text{Anteroposterior Acc} + 0.000244 \cdot \text{Cadence} \qquad (4)$$

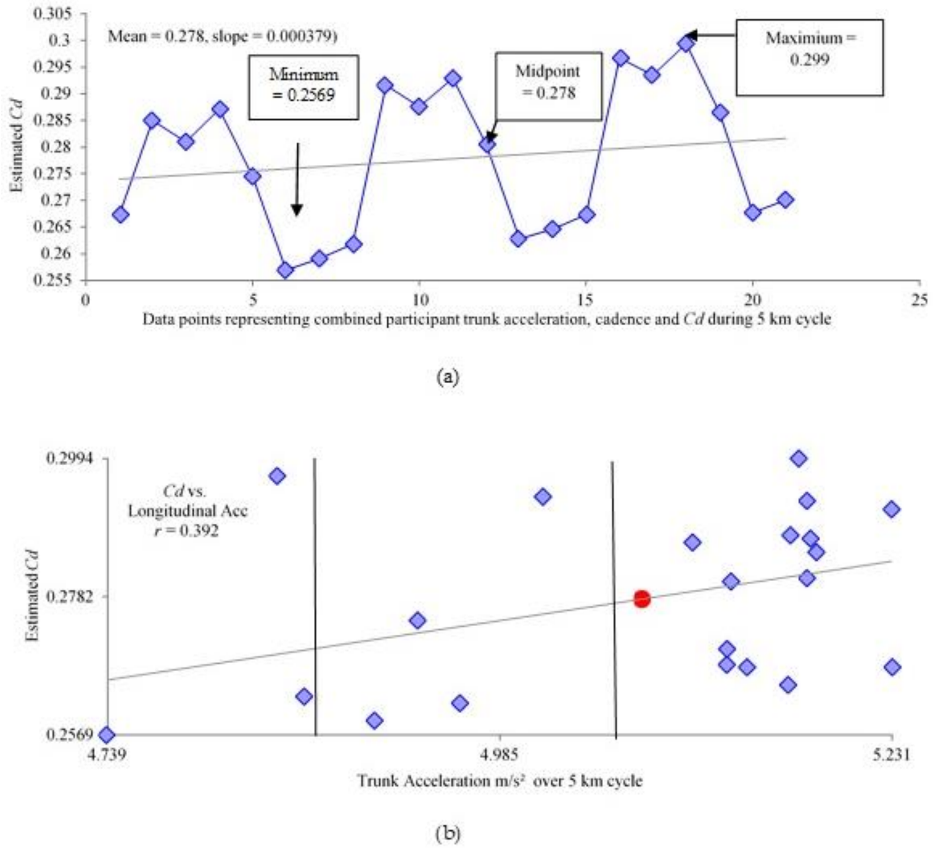

Figure 2. (a) Trunk acceleration and estimate of *Cd* based on overall mean cadence of 77 rev/min¹. (b) Longitudinal mean acceleration and estimated *Cd* over 5 km cycle.

DISCUSSION

The purpose of this preliminary study was to quantify kinematic determinants of triathlete cycling performance with linear trunk acceleration magnitude and cadence that contribute to *Cd* during overground cycling. It was hypothesised that a triathlete's average trunk acceleration would not predict level *Cd* time unless normalised to some representation of combined cadence and trunk acceleration. In this study, we obtained reference values for three cadence conditions as well as triaxial measurements of acceleration magnitudes of the trunk in a representative group of recreational triathletes who adopted an aerodynamic position when cycling for 5 km overground. Saddle position was adjusted to ensure uniformity amongst triathletes. Raw trunk acceleration data in longitudinal, mediolateral and anteroposterior directions based on changes to cadence was used to form a multivariable regression model to estimate the *Cd* to compare our triathletes' values with those obtained by other researchers.

Firstly, traditional cycling indexes such as power, delta and gross efficiency have typically been used to predict cycling performance with varying degrees of accuracy. Saddle height has been used in this realm given that is one aspect of bicycle setup that can dictate muscle activation (Ricard et al. 2006), joint kinematics (Price & Donne, 1997) and performance (Hamley & Thomas, 1967). The laboratory-to-field extrapolation of mechanical power has its drawbacks, including different environmental and/or physiological conditions between laboratory and field measurements (Brooks et al., 2000). It is also very difficult to reproduce a position on the bicycle and to obtain exactly the same aerodynamic drag values (García-Lopez et al., 2002).

In the present study, we observed significant differences to total trunk acceleration in the lower cadence of 55-60 rev/min[1], notably with higher intraindividual differences to longitudinal trunk acceleration. This increase may relate to weaker trunk strength in some triathletes that results in postural instability with some participants unable to apply effective pedal force to turn the crank. In this instance, a mean torque or force corresponds to a percentage of the maximum strength capacity that ultimately differs between participants (Bieuzen et al., 2007). This could be due to the maximal strength capacity of triathletes that influences trunk position at lower cadences levels.

The fitness level of the participants is an important consideration when evaluating why longitudinal and anteroposterior trunk acceleration increased at 95–100 rev/min[1]. It is known that with the increase in workload not only the amount of the force delivery, direction and efficiency on the pedals change, but also the application of the force to the saddle and handlebars (Stone & Hull, 1995). In other words, when the reaction forces on the pedals increase, weight is less supported by the saddle. Moreover, accelerations of the trunk, hips and shoulders will increase (Costes et al., 2015).

We had rationalised the inclusion of *Cd* into the model assuming that when cycling outdoors *Cd* could result in variations in cadence and therefore acceleration magnitudes. Unfortunately, there is no direct method for non-invasive measurement of acceleration magnitudes, *Cd*, and cadence, thus we decided to investigate how cadence impacts trunk acceleration whilst estimating drag using sensor technology. Because aerodynamic drag has been difficult to measure, many studies have endeavoured to use estimates of the FA to represent aerodynamic drag. The wind tunnel is the most valid and reliable technique (Hoerner, 1965), because it is sensitive to different types of handlebars, frames, and wheels in the same bicycle (Tew & Sayers, 1999). This preliminary study offers a theoretical and applied approach to using non-invasive sensors when observing trunk acceleration magnitudes and relationships to cadence and *Cd* during overground cycling. Typically, the drag coefficient of a cyclist ranges from ≈ min 10.6 for a streamlined time-trial position to > 0.8 for an upright position (Crouch et al., 2017). In this case, the more efficient time-trial position has the added benefit of a lower frontal area. We compared the modifications in drag area we obtained with those of other studies even if the methodology varied from one study to the other.

Obviously cycling speed depends on a number of factors that were assumed in this preliminary study in order to move at a certain speed. In most riding scenarios the aerodynamic drag accounts for the largest part of these forces. It is followed by the gravitational forces, the rolling resistance of the tires and mechanical losses of the bicycle drivetrain. Since one has to make quite a few assumptions, *Cd* was initially estimated based on prior recommendations. In the current study, the mean aerodynamic drag of 0.226 was taken as the reference value pertaining to 11.1 m/s (39 km/h) (Underwood et al., 2011). This value was based on triathlete capability. The best multiple regression model obtained with a single acceleration axis was longitudinal which accounted for 39% of the predicted drag in 5 km overground cycling. Cycling at a mean cadence of 77.19 rev/min¹ resulted in 33% correlation to drag. We did not observe any correlation between mediolateral acceleration nor anteroposterior trunk acceleration. The drag area values reported by Martin et al. (2006) were slightly lower than those in the present study. However, triathletes in our study were slightly lower in terms of comparable height and mass (1.77 m and 71.9 kg) which would have affected the power-to-weight ratio. Whereas Underwood et al. (2011) used a velodrome to obtain estimates the values presented for the highest cadence of 95–100 rev/min¹ was estimated to be 0.283 based on level ground cycling, similar to those reported by Jeukendrup (2002).

The individual modifications were apparent in both mediolateral and anteroposterior trunk acceleration, possibly associated with torso unsteadiness as both speed and drag increased. Although the higher cadence resulted in a 2.1% increase in aerodynamic drag compared to the 75-80 rev/min¹, ignoring the other resistances for the moment, our finding is that *Cd* is best estimated by longitudinal trunk acceleration by normalising cadence. While perhaps self-evident, this result underscores the significant absence of actual trunk acceleration magnitude data measures in studies attempting to estimate cycling time trial performance in the field.

When formulating the regression model, it is difficult to get accurate numbers for the rolling resistance coefficient and the drivetrain efficiency. Equally previous studies examined physiological and biomechanical responses when cyclists used aerodynamic handlebars but did not investigate the cyclists' adaptation to these positions. Additional considerations would include variable equipment (e.g., frame composite, wheels, spokes, clothes, and helmet). However, independent of prior methodological examination of trunk accelerations, overground cycling and the drag coefficient, our data could be an appropriate conduit for researchers and engineers when investigating trunk accelerations. Future research should attempt to model and compare field data collected in overground cycling that mimics race conditions with laboratory data. Hence, we consider that trunk acceleration is still an underreported technique to measure the aerodynamic drag in cycling. The practical applications of the study suggest that a triaxial accelerometer could be a viable tool to assist with modelling *Cd* in dynamic settings.

CONCLUSION

Trunk acceleration indicated high correlation with anthropometrics (stature, inseam), mechanical components (seat tube angle) and drag based on overground cycling. It seems that variations in cadence effects separate axis of acceleration magnitude rather than the cumulative effect. There is consistency in the predictive relationship between acceleration, inseam and saddle height whilst total trunk acceleration and *Cd* displayed a linear trend for greater acceleration magnitude and *Cd* in higher cadences. A combination of trunk acceleration, cadence and *Cd* can give us additional understanding of kinematical function, adaptation properties and dependency.

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