JOURNAL OF SPORTS SCIENCES
2025, VOL. 43, NO. 10, 995–1004
https://doi.org/10.1080/02640414.2025.2482356

Routledge
Taylor & Francis Group

SPORTS MEDICINE AND BIOMECHANICS

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A comparison between novice and elite cyclists movement stability during cycling

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ABSTRACT

The Lyapunov Exponent (LyE) is a non-linear technique that analyses stability, which refers to the capacity of systems to mitigate environmental perturbations. Whether elite athletes have an optimised movement stability is contentious. There has been limited research exploring the differences in movement stability using the LyE between elite and novice athletes. The purpose of this study was to compare movement stability between novice and elite male cyclists across a 4000 m bout, using the LyE. Participants completed two sessions of cycling (familiarisation and testing). Inertial measurement units were attached to the head, thorax, pelvis and left and right shanks to measure segment accelerations. The LyE was calculated using five, 100 cycle intervals across the bout. Elite cyclists had greater segment movement instability compared to novices at the head and pelvis in the longitudinal and medio-lateral direction, thorax in the medio-lateral and anterior-posterior direction and medio-lateral shanks. Both novice and elite cyclists demonstrated increased head, thorax and pelvis movement instability across the bout. This increase in instability across the bout may demonstrate the impact of fatigue on movement stability. Future research needs to now examine movement stability in the velodrome and explore the correlation between movement stability and aerodynamic drag.

ARTICLE HISTORY
Received 3 December 2023
Accepted 14 March 2025

KEYWORDS
Movement variability; stability; Lyapunov Exponent; cycling

Introduction

Dynamic systems theory (DST) suggests that task, environment and organism constraints influence movement expression (Davids et al., 2006; Kurz & Stergiou, 2004; Magill & Anderson, 2017). Thus, movement variability is considered normal and a function of health, allowing individuals to adapt to changing constraints (Davids et al., 2003; Newell & Corcos, 1993). Movement variability can be analysed using linear or non-linear methods (Harbourne & Stergiou, 2009; Stergiou & Decker, 2011).

Typically, linear methods have been used which focus on the magnitude of variability, by addressing how data is distributed about a mean with measures like standard deviation, coefficient of variation and range (Bradshaw et al., 2009; Wheat & Glazier, 2006). In doing so, linear measures assume each measurement point, for instance in gait, each step, is independent of one another and occurs at discrete intervals (Stergiou, Buzzi, et al., 2004). In doing so, by distilling a continuous variable into one metric, a large amount of information is disregarded that could be useful in explaining the movement patterns that have emerged (Preatoni et al., 2013). Therefore, linear measures do not evaluate the underlying structure of variability. Another limitation of linear measures is they can only measure one of the temporal or spatial aspects of movement, whilst neglecting the other component (Longo et al., 2018). In contrast, non-linear measures do analyse the structure of variability, and assume that movement patterns arise from a deterministic origin and acknowledge the influence of external and internal perturbations on movement patterns. As such, non-linear measures do evaluate the underlying structure of variability by examining variability across time and examine both spatial and temporal aspect of movement simultaneously (Longo et al., 2018; Smith et al., 2010; Stergiou, Buzzi, et al., 2004).

One of the more popular non-linear methods is the Lyapunov Exponent (LyE), which assesses local dynamic stability, the ability to attenuate local perturbations during cyclic movements (Abarbanel, 1996; Rosenstein et al., 1993; Wolf et al., 1985). It measures the divergence of neighbouring trajectories in a state space; the vector area where the dynamical system is defined (Mehdizadeh, 2019; Stergiou, Buzzi, et al., 2004). A larger, positive value signifies a greater variance in trajectories, indicating greater instability and conversely, a negative LyE indicates a stable system (Mehdizadeh, 2018; Stenum et al., 2014; Stergiou, Buzzi, et al., 2004). As such, lower values are desired, as it indicates greater stability. Primarily, LyE research has been limited to walking gait (Mehdizadeh, 2018), both in healthy and unhealthy individuals. Subsequently, research has applied the LyE to understand the factors that

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/02640414.2025.2482356

impact walking, like disease (Myers et al., 2009; Ricaurte et al., 2020), injury (Stergiou, Moraiti, et al., 2004), aging (Mehdizadeh, 2018) and secondary task performance (Hamacher et al., 2015) with seldom use in cycling (Winter et al., 2023).

The exact relationship between variability (linear measure) and stability (non-linear measure) is difficult to define (Longo et al., 2018) but typically, an increase in the magnitude of variability results in a decrease in stability (Smith et al., 2010). However, there exists instances where behaviours seem stable but exhibit high variability. For example, Dingwell and Marin (2006) found that at slower walking speeds, increased stability (decreased LyE values) was observed with an increase in magnitude of variability (standard deviation). Therefore, it can be inferred that the relationship between the magnitude of variability and structure of variability, defined by stability, is context dependent; and that variability and stability represent different concepts (Longo et al., 2018). Additionally, variability is neither inherently "good" or "bad". It has been suggested that a bandwidth of healthy variability exists, whereby if individuals are too variable, they possess instability and too little variability results in a rigid movement pattern (Stergiou & Decker, 2011). Within this healthy bandwidth, individuals can successfully navigate perturbations that may present.

According to DST, the neuromuscular system self-organises and selects the most efficient movement pattern to complete a task based on the contextual and environmental affordances, in order to effectively move (Kelso, 1984). However, a movement pattern that is efficient from a neuromuscular viewpoint, may not be the most optimal movement pattern to complete a task. The degree of stability required in a task is context dependent (Davids et al., 2006). Cycling may be an example where a high degree of stability is required.

To optimise cycling performance (cycle as fast as possible), cyclists must maximise their power output and reduce the aerodynamic drag that is experienced (Craig & Norton, 2001; Forte et al., 2020; Underwood, 2012). Riders have adopted the time trial (TT) position, which is a position characterised by an almost horizontal trunk position with one's hands and elbows placed on the handlebars (Crouch et al., 2017; Kordi et al., 2019). Cyclists adopt this position to reduce the frontal area and subsequently aerodynamic drag (Blocken et al., 2019). Theoretically, an increase in movement instability (increase in LyE) could negatively impact a cyclists' aerodynamic drag by increasing a cyclist's frontal area and coefficient of drag (Underwood, 2012).

The force a cyclist generates must be applied effectively to the pedals because forces applied orthogonal to the crank arm are converted to crank torque and subsequently bicycle velocity (Bini et al., 2013). Therefore, force should primarily be generated along the longitudinal and anterior-posterior axes (Bini & Carpes, 2014). This force and power production is dictated by the powers and moments that the cyclist produces at the lower body joints (Turpin & Watier, 2020). As such, decreased stability in the lower body and pelvis may alter power production, as could a decrease in trunk stability, as the trunk provides a stable support for the lower body to produce power (Elmer et al., 2011; Galindo-Martínez et al., 2021).

Currently, aerodynamics is assessed through wind-tunnels and computational fluid dynamics (CFD). Wind-tunnel testing provides a controlled, repeatable environment that mimics real world cycling conditions, but lack portability (Crouch et al., 2017). CFD requires complex mathematical modelling and is sensitive to numerous variables including the initial system conditions and turbulence models employed (Crouch et al., 2017; Debraux et al., 2011). As such, devising a technique that allows for portability to quantify aerodynamic drag would be invaluable to aid cycling performance.

LyE calculation has typically involved expensive optoelectronic measurement systems, which similar to methods that quantify aerodynamic drag, are lacking portability and require expertise to operate. Quantifying stability during cycling could be a valuable tool to understand performance by determining the body fluctuations of a cyclist, without direct assessment of drag and pedal force effectiveness. Examining differences in stability between elite and novice cyclists will further validate this method for analysing cycling performance.

This study aimed to compare the movement stability between elite and novice cyclists during the 4000 m time trial bout and determine if movement stability changed across the bout. It was hypothesised based on previous research on aerodynamics that novice cyclists will have decreased movement stability (higher LyE) at the head, trunk, pelvis and shanks segments compared to elite riders, as elite riders would be able to better constrain their movement (Underwood et al., 2011). It was also hypothesised that movement stability would decrease across the bout for all segments in both groups as it was predicted that it would be more difficult to maintain a rigid body position as the bout progressed.

Methods

Experimental overview

This study utilised a cohort study design following a similar experimental design as Winter et al. (2023). Participants completed two, 4000 m cycling trials, one familiarisation and one for analysis. During familiarisation, the Wattbike Pro (Wattbike, Wattbike Pro, Nottingham, UK) was prepared according to the participants' anthropometry. During the familiarisation trial, participants could alter the Wattbike resistance by adjusting the resistance lever to their preference. This was done to determine their desired resistance for the analysis session (Wattbike, 2015). This was kept constant to mitigate the effect of extraneous variables and was noted to aid with test replication and consistency. During the analysis session, IMUs were attached to participants. To mitigate the effect of fatigue and delayed onset muscle soreness, a minimum of 48 hours rest was provided prior to the analysis session being performed session which was similar to other research (Jongerius et al., 2022) and to align with American College of Sports Medicine (2023) recommendations. Testing took place at the University's biomechanics laboratory.

Participants

Two participant groups were recruited, elite and novice. A sample size of $n = 12$ was required as determined from a sample size calculation for an effect size of 0.35, alpha error of 0.05 and power of 0.8 with 2 groups and 5 measurements to have sufficient power to detect group x interval differences. Elite participants $n = 15$ (Mean ± SD, height (m), 1.85 ± 0.10, body mass (kg) 71.8 ± 6.5, age (yrs) 21.3 ± 3.6) were defined as those with maximal effort cycling experience, cycle a minimum of 120 km per wk (minimum of 5 hrs/week) as per Decroix et al. (2016) recommendations, and have familiarity with the time trial (TT) position (knowledge and prior experience riding in it). Novice participants $n = 36$ (Mean ± SD, height (m) 1.79 ± 0.07 m, body mass (kg) 77.3 ± 9.4 kg, age (yrs) 25.6 ± 4.5 yrs) were those who did not meet the elite criteria. Novice participants had varying cycling experience, ranging from 0 to 160 km per week. All participants had to pass stage 1 of the Exercise and Sports Science Australia exercise pre-screen, be aged between 18 and 35 yrs old, have prior maximal effort exercise experience and be injury free to their lower body for the previous 6 months to reduce the impact of injury on results and reduce injury risk. Ethics approval was obtained from the University's Human Research Ethics Committee prior to data collection (protocol number 204,077).

Protocol

Prior to testing, participants signed a consent form to provide informed consent. Prior to the familirisation trial, height and body mass was measured using a wall mounted stadiometer (SECA 216, Seca, Brooklyn, New York, USA) and digital scales (TANITA DR-953 Inner Scan Tanita, Tokyo, Japan), respectively.

Familiarisation

Following determining the participants height and mass, they underwent a bike fit, which was performed by the primary researcher to tailor the Wattbike to their individual anthropometry. Participants, whether elite or novice with a pre-established bike fit were permitted to replicate this on the Wattbike themselves, otherwise one was performed by the primary researcher. In the bike fit, saddle height was set at the participants' relative right knee flexion when at 25 degrees in the 6 o'clock crank position. This was performed with a goniometer. The centre of the goniometer was placed on the lateral femoral condyle, with the lower and upper arm of the goniometer pointing towards the lateral malleolus of the ankle and greater trochanter, respectively. To aid in determining this position, reflective markers were placed on the lateral malleolus, lateral femoral condyle and greater trochanter on their right side. To provide a guideline in determining saddle/fore aft position, the knee over the pedal spindle method was applied. In this method, the fore/aft position is determined when the participants' front knee is directly over the pedal spindle when the crank is positioned at the 3 o'clock position (Menard et al. 2016). This method was used as a guideline due to its lack of biomechanical justification, and participants could change this if required. Following this, participants moved into the TT position, where their hands and elbows are placed on the handlebars whilst assuming an almost horizontal trunk position (Kordi et al., 2019). To replicate the TT position for the analysis session, handlebar height, reach and separation were noted (Bini et al., 2020; Brand et al., 2020). Participants wore their own cleats/footwear and were attached to E-148 pedals. A strap accessory was applied for participants who did not possess cleats so their feet could be secure within the pedals. During familiarisation, a Wattbike profile was created for participants to collect power and time data which were later exported for analysis. To aid in familiarity with wearing IMUs, an IMU was placed on the right shank (just below the tibial tuberosity) during the familiarisation trial.

Analysis setup

Prior to the participants arrival, the Wattbike saddle height and fore/aft position and handlebar height was configured to their bike fit specifications. Participants wore tight, non-reflective clothing. Blue Trident IMUs (IMeasureU, Blue Trident, VICON, Oxford, UK) were attached to the participants' head (middle of the forehead), thorax (midline between the bottom of the sternum and the sternum notch), pelvis (between the posterior superior iliac spines), and one on the left and right shank (just below the tibial tuberosity), similar to other studies (de Jong et al., 2020; Lau & Tong, 2008; Tan et al., 2019), as seen in Figure 1. To ensure the IMUs remained fixated on the participant throughout the testing session, double-sided tape as well as strapping tape were applied over the IMUs. IMUs captured segment acceleration at 1200 hz longitudinal, medio-lateral (M-L) and anterior-posterior (A-P) accelerations were defined as X, Y and Z, respectively. Reflective markers were placed on the Wattbike's crank and pedal on the left and right side to determine when a pedal revolution was completed.

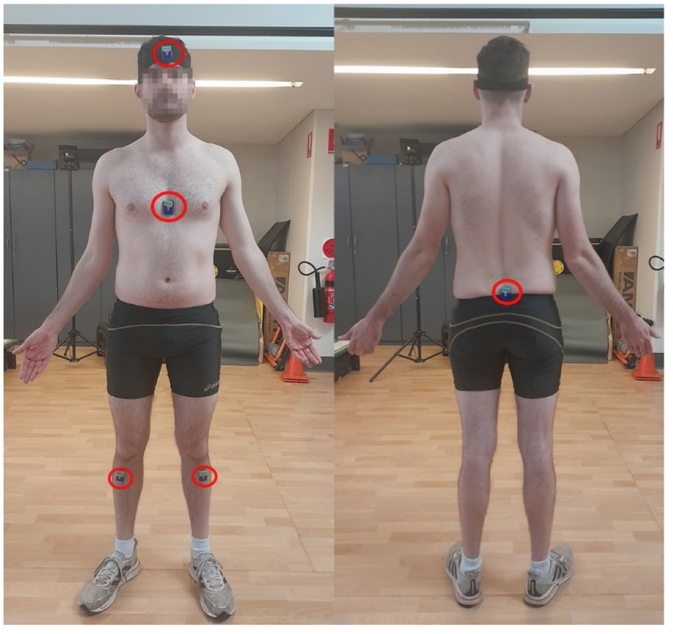

Figure 1. Placement of IMUs on the participant.

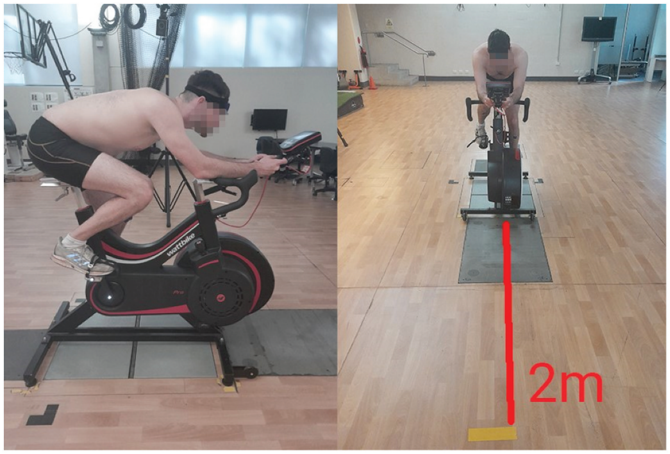

Figure 2. Sagittal and frontal view of the participant in TT position.

Cycling trial

Participants warmed up by cycling for 5 mins at a self-selected, resistance and cadence with a 5 s maximal intensity effort at the end (Glaister et al., 2015; Hibbert et al., 2017; Nakamura et al., 2020). Following a 3 min rest, the near maximal 4000 m cycling trial began. To mimic the push start in individual pursuit cycling, for the first 200 m, participants were out of the saddle, after which they assumed the TT position. Participants fixated their gaze on a piece of yellow tape that was 2 m in front of the Wattbike to better simulate a time trial bout (Figure 2). To aid in participants riding at a maximal intensity, verbal encouragement was provided. Following completion of the cycling trial, rate of perceived exertion (RPE) was assessed using the 1–10 RPE scale (Borg, 1998), to gauge participants subjective intensity.

To mitigate the effect of blood pooling and fatigue, at the completion of the cycling trial, participants cycled at low intensity for 3 mins, after which they could either statically stretch their lower body muscles or 'massage' their lower body with a foam roller (Seeley et al., 2021).

Data analysis

Cycling performance variables

Total time (mm:ss), mean power output (W) and cadence (rpm) were exported from Wattbike Expert (Wattbike Expert Ver 2.60.20). Within Microsoft Excel (Microsoft Corporation, WA, USA) power output and cadence was calculated at five intervals. This was done by separating the time values into five intervals, and power output was then averaged across these five intervals. The data corresponding to first 200 m was disregarded from analysis because it was not used in LyE calculation.

LyE

IMU data was exported from VICON Nexus. In Visual3D, start (TT position assumption) and end (completion of the trial) events were defined using the reflective markers attached to the Wattbike pedals. The first 200 m of the trial (where the participant was out of the time trial position), was disregarded because large shifts in position can affect stability results as calculated by the LyE. Filtering can negatively impact the ability to capture system instability by potentially removing 'real' fluctuations that occur, thus changing the dynamics of the systems (Raffalt et al., 2020). Therefore, IMU data was not filtered. A custom MATLAB code (The MathWorks, Inc., Natick, MA, USA) was written to calculate the LyE. Cycles were split into five, 100 cycle intervals; however, due to the differing times and resistances the participants rode at, instances occurred where 100 cycles could not be defined for the 5th interval. In these instances, the last pedal cycle was used to define the end point. Individual embedding dimension, m (number of successive points in the dynamical system) and time delay, τ (an integer determining how many data points are included for analysis) were defined for each variable in each interval, using the global false nearest neighbours method (Kennel et al., 1992) and determining the first minimum of the average mutual information function (Fraser & Swinney, 1986), respectively. Head m ranged from 3 to 4 and τ from 5 to 10. Thorax m was 4 across all axes and intervals and τ ranged from 7 to 10. Pelvis m and τ were 4 and 10 across all axes and intervals, respectively. Left and right shank m was consistently 4 across all axes and intervals, but τ ranged from 7 to 10 at the left shank and was consistently 10 at the right shank. Minimum and maximum m and τ for each segment axis and interval are reported in Tables S1–S3 in the supplementary materials. Following state space reconstruction, the LyE was calculated using the (Rosenstein et al., 1993) algorithm.

Statistical analysis

Statistical analysis was conducted using SPSS (v28, IBM Corp, New York, NY, USA). Box plots were used to determine if outliers existed. If after review, outliers were present, they were checked for errors and if no errors were found, the data was included for analysis. DST suggests that individuals can exhibit unique variability/stability and patterns of movement emerge based on the specific environmental, task and organism constraints (Davids et al., 2003). As such, removing an 'outlier' would not represent the data sample. Data was normally distributed as determined by a Shapiro and Wilk (1965) 'goodness of fit' and normality test. An independent samples t-test was conducted to compare bout completion time with an alpha set at 0.05. A linear mixed model with an alpha set at 0.05 was used to compare the effects of group (elite vs. novice) and intervals (1–5) during the cycling bout. If significant main effect differences were found, the least squared differences post hoc test was utilised, with an alpha set at 0.05.

Results

Due to the amount of data, tables are located within the supplementary materials and figures are used in text. Table S4 and S5 (located in the supplementary materials) contains the cycling performance variables and LyEs at each interval for each segment, respectively.

Cycling performance variables

Elite cyclists completed the 4000 m bout in less time than novices (6.27 mm:ss vs. 5.11 mm:ss; $p < 0.001$). Power (W) was

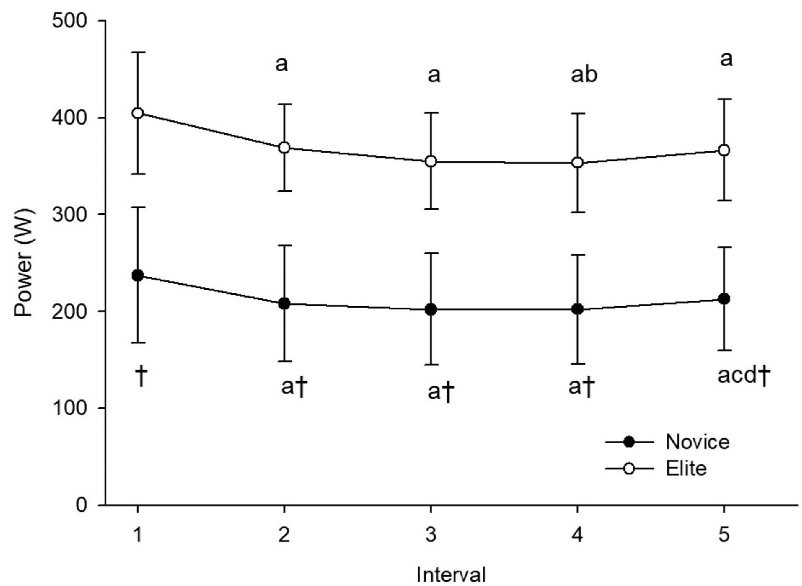

Figure 3. Power output for novice and elite participants across the 5 intervals. (a) $p < 0.05$ vs interval 1; (b) $p < 0.05$ vs. interval 2; (c) $p < 0.05$ vs. interval 3; (d) $p < 0.05$ vs. interval 4, † $p < 0.05$ vs. Elite.

greater ($p < 0.001$) in elite cyclists compared to novices in all 5 intervals (Figure 3). Novice cyclists power decreased ($p < 0.001$) in intervals 2–5 from interval 1 but increased ($p < 0.05$) from intervals 3 ($p = 0.030$) and 4 ($p = 0.032$), to interval 5 (Figure 3). Similarly, elite cyclists power decreased ($p < 0.001$) in intervals 2–5 from interval 1 and from interval 2–4 ($p = 0.050$) (Figure 3). Cadence (RPM) was greater ($p < 0.001$) in elite cyclists compared to novices in all 5 intervals (Figure 3). Novice cyclists cadence decreased ($p < 0.001$) in intervals 2–5 from interval 1 and decreased from intervals 3 ($p < 0.004$) and 4 ($p < 0.006$) to 5. Similarly, elite cyclists cadence decreased ($p < 0.001$–0.018) in intervals 2–5 from interval 1. Elite participants and novice cyclists reported an average RPE of 9.17 and 8.83, respectively, suggesting that both groups rode at near maximal intensities during the 4 km bouts.

LyE

Head

Longitudinal head (Figure 5(a)) and M-L (Figure 5(b)) LyE increased from interval 1 vs. intervals 2–5 ($p = < 0.001$–0.045), from interval 2 vs. intervals 3–5 ($p = < 0.001$–0.06) and from interval 4 vs 5 ($p = < 0.001$–0.006) for both novice and elite cyclists, respectively. Both Longitudinal (Figure 5(a)) and M-L (Figure 5(b)) head LyE increased from interval 3 vs. 4 ($p = < 0.001$–0.013) in novice cyclists. Elite cyclists had greater ($p < 0.024$) M-L head LyE than novice cyclists in interval 5 (Figure 5(b)) and greater ($p < 0.001$) longitudinal acceleration in all intervals (Figure 5(a)).

Thorax

In both novice and elite cyclists, thorax M-L LyE (Figure 5(e)) increased ($p = < 0.001$–0.003) from interval 1 vs. intervals 2–5, from interval 2 & 3 vs. intervals 4 and 5 ($p = < 0.001$–0.017) and from interval 4 vs. 5 ($p < 0.001$). Additionally, novice cyclists M-L LyE (Figure 5(e)) increased from interval 2 vs. 3 ($p = 0.018$). Both novice and elite cyclists A-P thorax LyE increased ($p < 0.05$) from interval 1 vs. intervals 2–5 ($p = < 0.001$–0.033) and from intervals 2 vs. intervals 4 and 5 ($p = < 0.001$–0.021), and from interval 3 vs. 5 ($p < 0.001$). Elite cyclists also increased ($p < 0.05$) in LyE from interval 4 vs. 5 ($p = 0.041$), and novice cyclists increased ($p < 0.05$) from interval 3 vs. 4 ($p = 0.010$). Elite cyclists had greater ($p < 0.05$) M-L ($p < 0.001$ - Figure 5(e)) and A-P thorax ($p = < 0.001$–0.004) -Figure 4(f)) LyE than novice cyclists in all intervals.

Pelvis

Pelvis longitudinal LyE (Figure 5(g)) decreased ($p < 0.05$) from interval 1 vs. intervals 2–4 ($p = < 0.001$–0.005) but increased ($p = 0.032$) from interval 3 vs. 5 in novice cyclists. Conversely, elite cyclists increased in longitudinal pelvis LyE from intervals 2 ($p = 0.018$) and 3 ($p = 0.011$) vs. interval 5. M-L pelvis LyE (Figure 5(h)) increased ($p < 0.05$) from interval 1 vs. 5 ($p < 0.001$) and from interval 2 vs. 4 in novice cyclists ($p = 0.014$). In both novice and elite cyclists, M-L pelvis LyE increased ($p < 0.05$) from intervals 2–4 vs. interval 5 ($p = < 0.001$–0.025). Elite cyclists had greater ($p < 0.05$) longitudinal ($p = < 0.001$–0.05 - Figure 5(g)) and M-L ($p < 0.001$ - Figure 5(h)) pelvis LyE than novice cyclists in all intervals.

Shank

M-L right shank (Figure 6(b)) increased from interval 1 vs. 5 ($p = 0.022$) in elite cyclists. Elite cyclists had greater M-L right shank LyE ($p = 0.007$–0.022) than novice cyclists in all intervals. In novice cyclists, M-L left shank LyE (Figure 6(e)) decreased from interval 1 vs. intervals 2 ($p = 0.036$) and 3 ($p = 0.030$) whereas in elite cyclists, M-L left shank LyE increased from interval 1 vs. intervals 2–5 ($p = <$

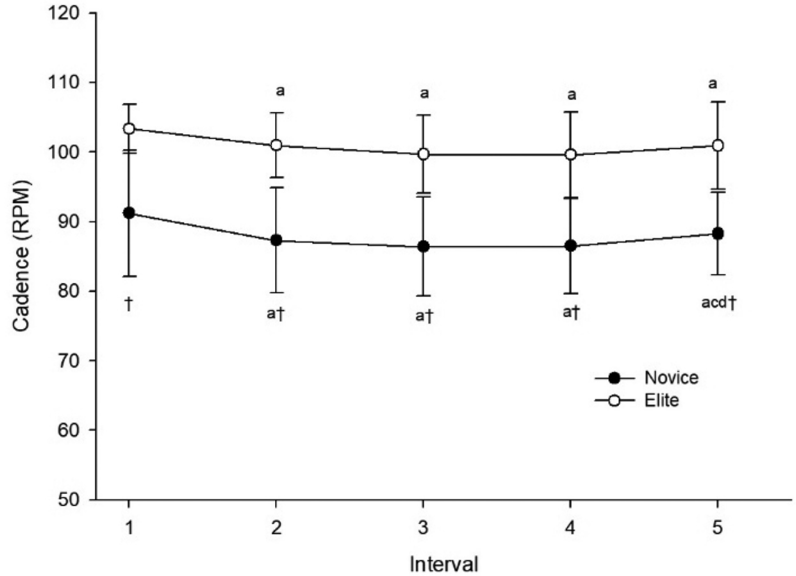

Figure 4. Cadence for novice and elite participants across the 5 intervals. (a) $p < 0.05$ vs interval 1; (c) $p < 0.05$ vs. interval 3; (d) $p < 0.05$ vs. interval 4, † $p < 0.05$ vs. Elite.

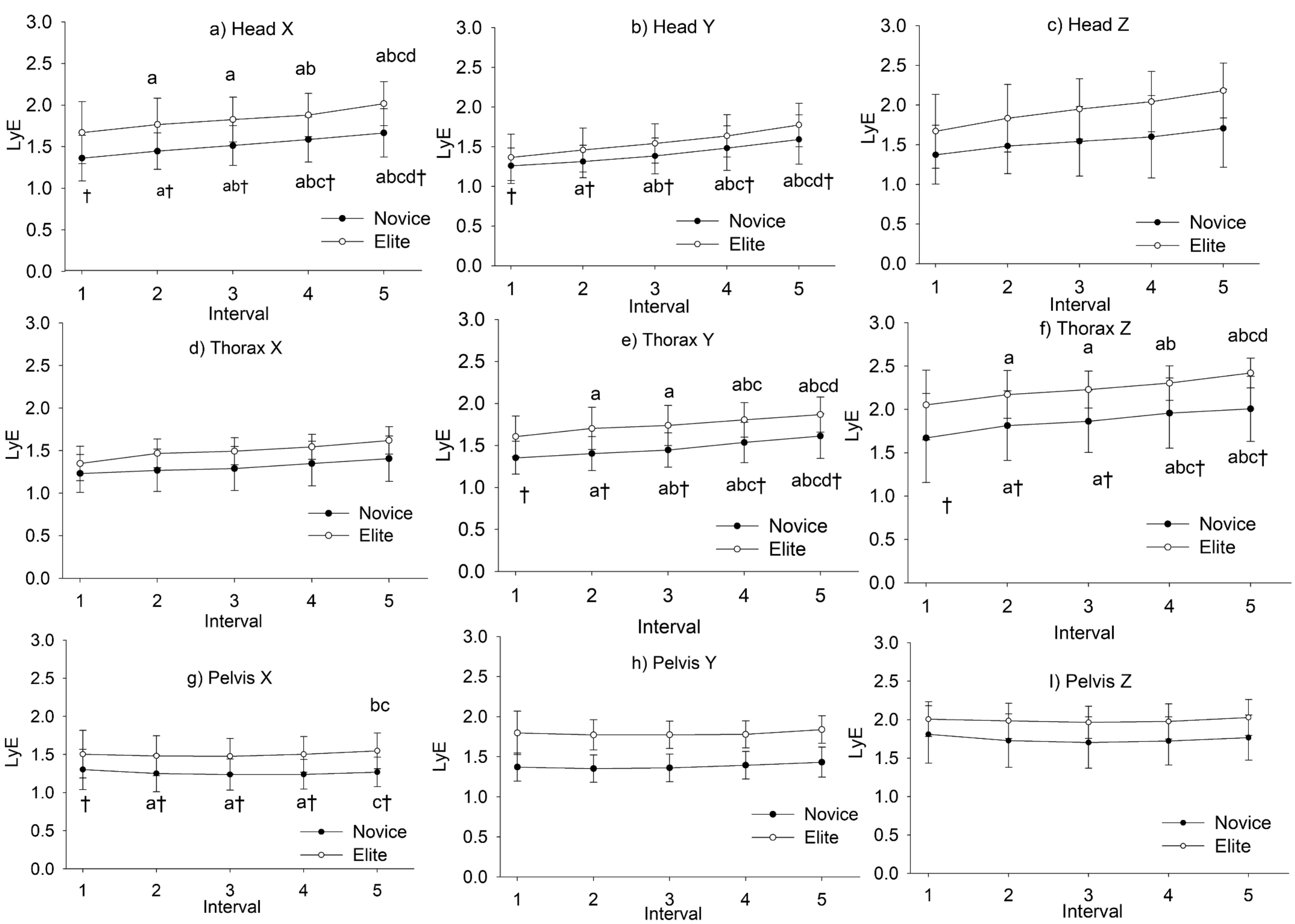

Figure 5. Head, thorax, pelvis movement LyE for novice and elite participant across the 5 intervals (X – longitudinal axis; Y - medio-lateral axis; Z – anterior-posterior axis). (a) $p < 0.05$ vs interval 1; (b) $p < 0.05$ vs. interval 2; (c) $p < 0.05$ vs. interval 3; (d) $p < 0.05$ vs. interval 4, †$p < 0.05$ vs. Elite

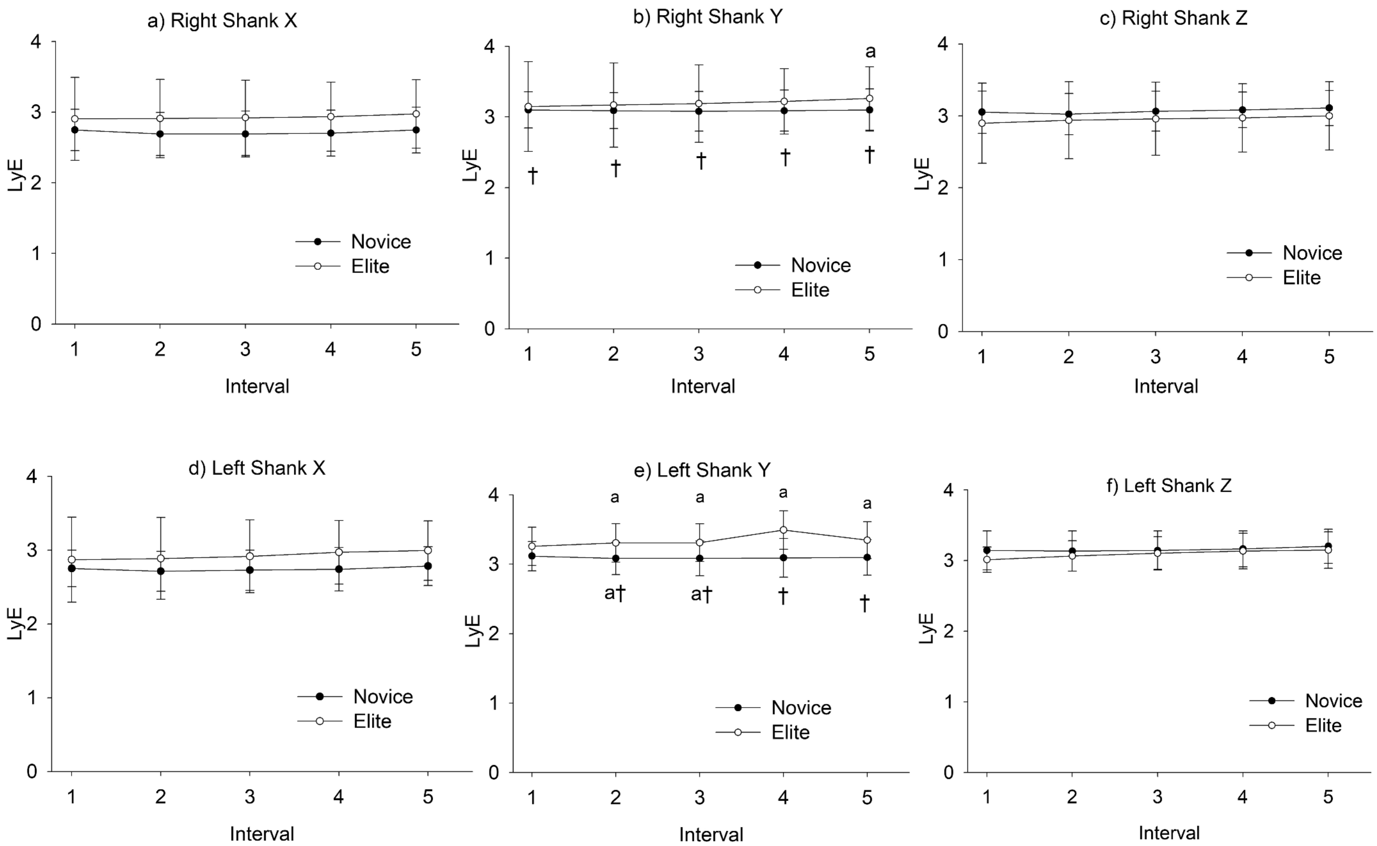

Figure 6. Left and right shank LyE values for novice and elite participants across the 5 intervals (X – longitudinal axis; Y - medio-lateral axis; Z – anterior-posterior axis). [a]$p < 0.05$ vs interval 1, [†]$p < 0.05$ vs. Elite.

0.001–0.028). Elite cyclists exhibited greater M-L left shank LyE than novice cyclists from intervals 2–5 (p = 0.002 to 0.005).

Discussion

This study aimed to investigate whether differences in movement stability existed between elite and novice cyclists and if movement stability changed during a 4000 m cycling bout. It was expected that elite cyclists would exhibit increased stability, indicated by a reduced LyE at all segments due to their greater cycling experience and greater ability to constrain their movement. The hypothesis was not supported. Elite cyclists exhibited increased head, thorax, pelvis and shank movement instability compared to novices. Additionally, it was hypothesised that movement stability would increase across the intervals in both groups. A consistent increase in head and thorax movement instability occurred across the bout whilst pelvis (besides M-L pelvis acceleration) and shank movement stability remained consistent. Therefore, the hypothesis was supported.

As expected, elite cyclists exhibited higher power outputs across the bout, culminating in quicker bout completion than novices. Both novices and elite cyclists exhibited the same pattern in power, peaking in the first interval and decreasing across the bout, but slightly increasing from internal 4 to 5, potentially highlighting the impact of fatigue. The increase in power output at the end of the bout could be a result of a shift in pacing strategy as participants neared exercise completion. This may have occurred because participants were not blinded to the distance they had travelled (St Clair Gibson et al., 2006).

Longitudinal and M-L head, and M-L and A-P thorax movement instability, respectively, increased across the bout, highlighting the potential impact of fatigue in both novice and elite cyclists. Elite cyclists demonstrated greater head and thorax movement instability than their novice counterparts. Therefore, the initial hypothesis that was made that elite cyclists would exhibit improved stability was not supported. It was initially thought that head and thorax movement stability should be increased to minimise the potential negative impact on aerodynamic drag by increasing a cyclist's frontal area (Underwood et al., 2011). Similarly, the M-L left shank and M-L and longitudinal right shank movement instability was higher in elite cyclists than novices. Similar to the head and thorax, it was initially theorised that an increased lower body shift, particularly in the M-L direction, would hinder a cyclists ability to produce effective pedal force and subsequently reduce power output. As such, it was thought that elite cyclists would constrain their lower body instability. However, the results obtained do not support this.

The increase in instability that occurred in elite cyclists compared to their novice counterparts is likely due to the environment where the testing took place. In accordance with DST, environmental constraints influence movement patterns. Cowin et al. (2022) suggested that sporting tasks should be assessed within ecologically valid domains because removing tasks from their original setting can lead to different movement patterns being exhibited. Commensurate with this idea, ergometers are stationary and do not permit side to side movement, thus possessing different constraints to a regular bicycle, which could impact the movement patterns of a cyclist and subsequently performance (Wilkinson & Lichtwark, 2021; Wilkinson et al., 2020). As such, because testing occurred in a research laboratory on a Wattbike where aerodynamic drag has no impact on performance, rather than a velodrome where drag is a factor, elite cyclists may have cycled differently. Elite cyclists who are aware that drag was not an influencing factor on power output may have solely focused on power expression without concern for their drag profile. This may have resulted in them consistently exhibiting greater movement instability by shifting their upper and lower body positioning to attempt to shift greater body weight to the pedals (Sayers & Tweddle, 2012; Wilkinson & Kram, 2021). To confirm this, further research should be conducted in a velodrome to determine the impact of environment on movement stability. If differences are present in the LyE between the laboratory and velodrome condition, then the impact of environment is highlighted. Additionally, future research is required to be undertaken in wind tunnels to confirm the effect of increased movement instability on aerodynamic drag prior to this method being implemented in practice and competition as currently, definitive conclusions cannot be made regarding its effect. Furthermore, future studies should address the reliability of the LyE in elite cyclists which has yet to be addressed, to determine if changes in movement stability that were observed would consistently exist across sessions in elite cyclists. This study, based on the principles of DST allowed the participants to self-select their resistance and cadence so they better adopted their natural cycling pattern.

The differences in LyE that exists between novices and elite cyclists could be due to the differences in power and cadence. Potentially, the overall increase in instability at the head, thorax and M-L left shank and M-L and longitudinal right shank could have been due to the increase in cadence and power expression. Participants in this study could cycle at their preferred cadence and to allow for more 'normal' movement patterns to emerge and were instructed to complete the bout as fast as possible. Cadence (or steps per minute in running) and power has typically been controlled for in studies using the LyE and little research has assessed its impact on the LyE. Russell and Haworth (2014) concluded that walking at a preferred stride frequency elicited lower LyE values, however the impact of cadence on running or cycling has not been assessed. Mehdizadeh, Arshi et al. (2016) concluded that running speed did not affect the LyE when running above or below preferred running speeds; however, the speeds at which these individuals were running were not at their maximum, unlike the participants in this study who cycled at a maximum intensity. Conversely, Look et al. (2013) found that LyE values increased as speed increased in running; however, only 8 strides were captured. Future research needs to control for cadence and power at multiple rates riding in the same position to better elucidate the impact of cadence and power on the LyE in cycling. Further investigation could analyse the affect of different resistance in movement stability as quantified by the LyE, given that resistance, like cadence effects how power is expressed (Zameziati et al., 2006). This study confirmed that increases in instability occurred across a bout, which occurred as power output decreased, suggesting that instability increases as one fatigues. However, further research is required to better elucidate potential performance links to drag and power before this method is applied in training and competition scenarios.

Conclusion

This study was the first to the authors' knowledge that has examined differences in elite and novices movement instability during a cycling bout using IMUs. Increased movement instability was reported at the head, thorax, pelvis and shanks in elite cyclists compared to novices. Additionally, it was shown that both novice and elite cyclists increase their head and thorax movement instability across a bout, without altering pelvis and shank stability, which may have detrimental effects on aerodynamic drag in a velodrome environment. However, prior to capturing movement instability in training and competition scenarios via the LyE, future research should investigate the relationship between the LyE and aerodynamic drag in wind-tunnels and the impact of environment on movement stability calculated with the LyE, to better determine the practicality of the method.

Acknowledgements

The authors are grateful to the participants that volunteered to participate in the study.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee [protocol number 204077, approved December 2021].

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Conceptualisation, L.W., P.G., C.B. and R.G.C.; Data curation, L.W.; Formal analysis, L.W. and R.G.C.; Investigation, L.W., R.G.C.; Methodology, L.W., P.G., C.B., and R.G.C.; Project administration, L.W. and R.G.C.; Resources, R.G.C.; Software, L.W. and R.G.C.; Supervision, P.G., C.B., and R.G.C.; Validation, L. W. and R.G.C.; Visualisation, L.W.; Writing – original draft, L.W.; Writing – review and editing, P.G. C.B. and R.G.C. All authors have read and agreed to the published version of the manuscript.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Data availability statement

Data are available on request to the corresponding author.

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