Sports Biomechanics

ISSN: 1476-3141 (Print) 1752-6116 (Online) Journal homepage: www.tandfonline.com/journals/rspb20

Exploring the reliability of isometric benchmark tests and their relationship to performance characteristics in elite track sprint cyclists

Roné Thompson, Carl Paton, Rodrigo Rico Bini & Kim Hébert-Losier

To cite this article: Roné Thompson, Carl Paton, Rodrigo Rico Bini & Kim Hébert-Losier (08 Dec 2025): Exploring the reliability of isometric benchmark tests and their relationship to performance characteristics in elite track sprint cyclists, Sports Biomechanics, DOI: 10.1080/14763141.2025.2593325

To link to this article: https://doi.org/10.1080/14763141.2025.2593325

SPORTS BIOMECHANICS
https://doi.org/10.1080/14763141.2025.2593325

Routledge
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS Check for updates

Exploring the reliability of isometric benchmark tests and their relationship to performance characteristics in elite track sprint cyclists

Roné Thompson [a,b], Carl Paton [c], Rodrigo Rico Bini [d] and Kim Hébert-Losier [a]

[a]Division of Health, School of Sport and Human Movement, University of Waikato, Adams Centre for High Performance, Tauranga, New Zealand; [b]Performance Health, High Performance Sport New Zealand, Grassroots Trust Velodrome, Cambridge, New Zealand; [c]School of Health and Sport Science, Te Pukenga at Eastern Institute of Technology, Napier, New Zealand; [d]Holsworth Biomedical Research Centre, La Trobe Rural Health School, Bendigo, Victoria, Australia

ABSTRACT

Benchmark tests in competitive cycling identify talent, individualise training, and monitor performance. However, varying protocols often produce conflicting results, reducing comparability. Isometric tests are prevalent, but reliability and performance correlation are underexplored. Determine the test–retest reliability of benchmark test metrics in elite track sprint cyclists and their relationship to a performance outcome. Nineteen elite track sprint cyclists (12 males, 7 females) completed seven benchmark tests across two days: modified sit-and-reach; on-bike rolling seated maximum 6-s sprints; 3-s bilateral on-bike isometrics at 90° crank angle; 3-s prone bench pull isometrics; 3-s lumbar extension isometrics; 3-s seated off-bike isometrics; and modified plank endurance. For the performance outcome, a third session within 7 days assessed peak power using an inertial load cycle ergometer. All tests showed *excellent* measurement consistency ($ICC_{3,1} \geq 0.92$), with low systematic bias ($p \geq 0.063$), though confidence interval varied due to modest sample size. High test–retest reliability was supported by low typical errors (CV 2.0–5.5%; 9.6% for endurance). Nine benchmark metrics, including bilateral isometric measures, showed moderate to excellent correlation with peak power output ($r = 0.52$–0.94, $p \leq 0.023$); six remained statistically significant after Bonferroni correction ($p \leq 0.005$). All benchmark metrics were reliable, with six strongly and statistically significantly associated with performance.

ARTICLE HISTORY
Received 2 April 2025
Accepted 17 November 2025

KEYWORDS
Isometrics; performance; reliability; track sprint cyclists

Introduction

Cycling is a significant sport at the Summer Olympic Games. Cycling was the second most researched sport during the 2021–2022 Summer and Winter Olympics, following football, resulting in many scientific articles and related citations (Millet et al., 2021). Track sprint cycling events have received less research attention compared to endurance cycling. It

CONTACT Roné Thompson rt275@students.waikato.ac.nz; rone.thompson@hpsnz.org.nz
Supplemental data for this article can be accessed online at https://doi.org/10.1080/14763141.2025.2593325

manifests typically on a velodrome track of 333 m or less and generally consists of endurance (> 1000 m) and sprint (≤1000 m) events (Craig & Norton, 2001). The Olympic Games currently host three events for track sprint cycling: Team Sprint, Match Sprint, and Keirin. Most sprint cyclists would compete across these events, despite their unique technical, tactical, and physiological requirements (Douglas et al., 2021). The fastest speeds on the track are achieved through higher power output from the cyclists, alongside a decreased resistance source, including rolling resistance and air resistance (Craig & Norton, 2001).

Elite track cyclists frequently undergo testing batteries to assess injury risk and monitor performance. However, there is a lack of evidence for the effectiveness of tests to predict injuries within sports (Bahr, 2016). Even though sports injuries or illnesses considerably affect performance (Raysmith & Drew, 2016), large sample sizes are needed to identify trends in injury incidences (Chandran et al., 2019). Focusing on the use of benchmark tests related to performance may be more appropriate in elite settings than injury risk screening ones, as the former can assist in evaluating physical capabilities of athletes, identifying talent, longitudinal monitoring, and informing exercise prescription (Weakley et al., 2024). However, for benchmark tests to be worthwhile, the tests need to be reliable and valid (Weakley et al., 2024) with reference to performance.

Elite cyclists experience considerably high loads and frequent daily training blocks. Without adequate recovery, benchmark testing that increases high training load can have a detrimental effect, particularly on force production and motor control (DiDomenico & Raiola, 2021). Therefore, reliability of benchmark tests might be compromised and prove difficult to implement due to rigorous periodisation plans if these tests are not carefully selected and timed.

Isometric contraction involves the contraction of skeletal muscles without changes in joint angles (Lum & Barbosa, 2019). Benchmark tests that focus mainly on isometric exercises may be beneficial, as these are easier to administer with no need to control the speed or range of movement, and cause less fatigue than dynamic exercises (Smajla et al., 2024). Using isometrics for benchmark tests, supports the recovery-fatigue continuum, enhancing training quality and presumably limiting injury risk (Kellmann et al., 2018). Isometric training has previously been shown to increase power output in track sprint cyclists (Kordi et al., 2020). In addition, Isometric training has many applications in track sprint cycling, including pain management and improving tendon properties at the knees (Kubo et al., 2006; Marks, 1993; Rio et al., 2017), enhancing high-velocity training response or rate of force development (Behm & Sale, 1993; Lum & Barbosa, 2019), and optimising dynamic strength (Folland et al., 2005; James et al., 2023; Lum et al., 2020).

Despite the common use of isometrics in cycling (Kordi et al., 2020, 2021; Kruger et al., 2019) and the established reliability of the isometric mid-thigh pull test and its correlation to peak force (Grover et al., 2024; Stavridis et al., 2025; Stone et al., 2004), there is still lack of information on the reliability of isometric tests in elite track sprint cyclists and on how these measures relate to cycling-specific performance metrics. Therefore, the aim of this investigation was to quantify the test–retest reliability of seven predominantly isometric benchmark tests in elite sprint track cyclists, and to establish the relationship between the outcomes from these tests and a track cycling specific peak power performance test. In our study, the custom-built inertial load cycle ergometer was set as the main sprint cycling specific performance outcome given it is an evidence-based reliable method used to assess maximum power output capabilities in this sport (Gardner et al., 2007; Martin et al., 1997; Wickwire et al., 2011). A secondary aim was to explore the interrelatedness between benchmark tests, as establishing their relative interchangeability would allow flexibility for future testing, pending equipment availability.

Materials and methods

Participants

All elite track sprint cyclists in New Zealand, classified as currently competing at competitions sanctioned by the Union Cycliste Internationale (Phillips & Hopkins, 2020), were recruited through flyers and personal communication to the sports national governing body ($N = 23$). In total, 19 cyclists agreed to participate, representing 90% of the eligible population. Cyclists specialised in events contested at the Olympics (Match sprint, Keirin, and Team sprint), with two cyclists competing at a junior level (U/19) and eight embedded full-time within the National performance track cycling programme (Table 1). All cyclists provided written consent before participating and were informed of risks (e.g., musculoskeletal injury or delayed onset of muscle soreness) and benefits (e.g., individualised report on performance metrics). The Human Research Ethics Committee of the University of Waikato granted ethical approval before participant recruitment (2023#28). Given reliability was expected to be *excellent* (intraclass correlation coefficient, ICC = 0.90), considering the isometric nature of the tests (Grgic et al., 2022; Grover et al., 2024) and elite nature of performers, the sample size of 19 provided our 0.90 ICC estimate a precision of ±0.09, with a confidence level of 95% (Borg et al., 2022).

Protocol

The cyclists visited the experimental venue three times over a seven-day period. All cyclists completed seven benchmark tests in the same manner and order on day one and day two of testing. Participants did not train immediately before testing, with a minimum of 48 hours and a maximum of 96 hours between the two days. The third testing day involved all cyclists completing a maximum seated inertial load cycle ergometer test (Martin et al., 1997). The custom-built inertial load cycling ergometer used methods outlined in previous research to obtain their maximum power output (Martin

Table 1. Characteristics (mean ± SD) of the 19 elite cyclists completing the benchmark and peak power inertial load ergometer tests.

	Elite M	Elite F	Para cyclists M	Para cyclists F
	$N = 10$	$N = 6$	$N = 2$	$N = 1$
Age (y)	20.4 ± 2.8	21.5 ± 2.9	18.5 ± 0.7	31.0
Mass (kg)	84.3 ± 8.3	71.5 ± 10.1	81.2 ± 7.0	58.6
Height (cm)	180.0 ± 6.6	171.1 ± 6.7	180.1 ± 1.7	170.1
Sum of 8 SF (mm)	60.4 ± 16.3[†]	97.7 ± 16.5[†]	131.1 ± 40.3	77.8
BMI (kg/m^2)	26.1 ± 2.9	24.3 ± 1.8	25.0 ± 1.7	20.3
PPO (W)	1658.84 ± 196.17	1186.83 ± 245.95	1122.50 ± 253.85	740

Notes. [†] Data missing from one cyclist since no skinfold measurements took place with the U/19 cyclists as per National governing body recommendations. Abbreviations: BMI, body mass index; F, female; M, male; PPO, peak power output; SF, skinfolds.

et al., 1997). The peak power output of sprint cyclists correlates well with sprint track cycling performance (Gardner et al., 2007; Kordi et al., 2019; Martin et al., 1997). The inertial load cycle ergometer test (Wickwire et al., 2011) was completed on a day over the seven days, either before or after the benchmark testing days.

The same researcher delivered the testing protocol and collected all the data in the High Performance physiotherapy clinic and gym of the National Training Centre. An accredited International Society for the Advancement of Kinanthropometry (ISAK) Level 2 Performance nutritionist collected anthropometric measures from all cyclists following standardised ISAK protocols (Ros et al., 2019) within 24 h of day one testing following an overnight 12-h fast.

Testing process

Cyclists completed a generic warm-up, which consisted of five minutes of cycling on their track bike on the ergometer (LeMond Bicycle Inc.) between 100 and 150 watts at 80–120 revolutions per minute (rpm), followed by one set of six repetitions of double leg bent over rows, squats, and Romanian deadlifts with 20 kg. Before starting each benchmark test, the cyclists perform a familiarisation repetition at 50% effort to ensure they felt comfortable with the maximum execution of each test. The seven benchmark tests completed in the same order were: 3-s hold modified sit-and-reach test; on-bike rolling seated maximum 6-s sprints; 3-s bilateral on-bike isometrics at a 90° crank angle; 3-s prone bench pull isometrics; 3-s lumbar extension isometrics; 3-s seated off-bike isometrics with bilateral forefoot push and bilateral upper limb pull (mimicking on-bike isometrics position); and a modified plank endurance test (Table 2). The testing protocol for all isometric tests consisted of three 3-s maximal contractions, separated by a 30-s recovery. In line with published research (O'Neill et al., 2023) we determined that isometric peak force should be generated within three repetitions, and anything longer than a 30-s recovery would not increase force output (O'Neill et al., 2023). For the on- and off-bike isometrics, a 60-s rest was provided between legs to allow for position changes. The modified plank test measured the maximum isometric hold only once due to fatigue. We implemented a 5-minute passive recovery between repetitions of the on-bike rolling starts and a 5-minute passive recovery between the different benchmark tests. Cyclists first tested their preferred starting leg for the team sprint event during unilateral tests. The order of all tests and starting legs was constant on both testing occasions.

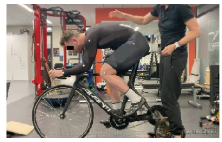
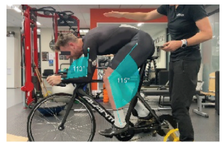
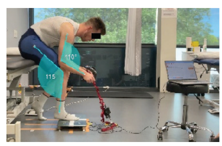
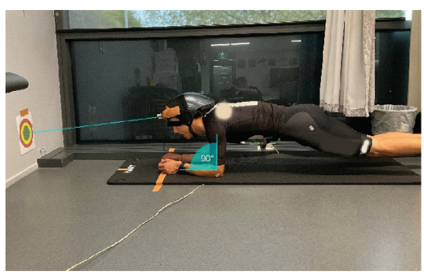
Data collection and processing

The procedures for the benchmark and track cycling-specific tests conducted in this study are summarised in Table 2. All seven benchmark tests were filmed using an iPad Pro 10th generation iOS 15.41 (Apple Inc) to verify correct positioning in the sagittal view. Data for a given repetition were excluded when incorrect positions were observed.

Modified sit-and-reach test

A custom-built board with straps was used to place the knees at 30° of flexion (Table 2) to reflect the commonly reported ranges of knee flexion angles of cyclists at the bottom dead

Table 2. Description of the seven benchmark tests and inertial load cycle ergometer used with our elite cyclists.

Test[†]	Reps and rest[‡]	Instructions	Equipment	Image
3-s hold modified sit-and-reach test	3 x with 30 s rest between reps	Reach as far as possible and hold for 3 s.	Sit-and-reach box and customised 30° knee flexion board	
On-bike rolling seated max 6-s sprint	3 x with 5-min rest between reps	Slow spin for a few pedal cycles, then standardised instructions to accelerate as fast as possible for six seconds. Stay seated and keep your normal on-bike racing position.	Avanti Co. 84-inch gear track bike on a LeMond Revolution cycle ergometer equipped with a SRM Science Track Power Meter	
3-s bilateral on-bike isometrics at 90° crank angle[§]	3 x with 30 s rest between reps and 60 s rest between legs	Push with your front leg and pull with your back leg as hard as possible, like you would on a bike. Stay seated and keep your normal on-bike racing position.	Avanti Co. 84-inch gear track bike on a custom-built isometric cycle ergometer	
3-s prone bench pull isometrics	3 x with 30 s rest between reps	Pull as hard as you can with both hands, keeping your head and spine aligned. Do not fixate your feet.	Adjustable gym benches with foot catch and wireless load cell attached to bench pull handlebars and anchored to the floor	
3-s lumbar extension isometrics	3 x with 30 s rest between reps	Pull as hard as possible towards the ceiling, maintaining your arms across your chest.	Adjustable gym benches with foot catch and wireless load cell attached to a thoracic vest and anchored to the floor	
3-s seated off-bike isometrics with bilateral forefoot push and upper limb pull[§]	3 x with 30 s rest between reps and 60 s rest between legs	Stay seated while pushing down as hard as possible with your front foot, using your back foot for balance. At the same time perform a maximum pull on the handlebars in the set elbow angle.	Adjustable plinth, force plates, and wireless load cell attached to handlebars and anchored to the floor	
Modified plank test	1 x maximal hold	Maintain a neutral prone plank position for as long as possible, with only the forearms and toes in contact with the yoga mat. Shoulders need to be over the (90°) bent elbows, and the head needs to be positioned to mimic your race position. Point the laser in the middle of the target (bullseye) and keep it there.	Yoga mat, wall-affixed target, a laser mounted to their own sprint helmet, and a  stopwatch	

(*Continued*)

Table 2. (Continued).

Test†	Reps and rest‡	Instructions	Equipment	Image
Maximum seated inertial load cycle ergometer test	3 x max efforts with 5min rest between reps	Stay seated and perform a maximum effort sprint lasting 4 to 6 s	Custom-built inertial load cycling ergometer	

Notes. †Order of the tests held constant between cyclists. ‡Five-minute passive rest between benchmark tests. St Preferred starting leg for team sprint was the first leg tested for all cyclists (85% left leg). Abbreviations: max, maximum; reps, repetitions.

centre of pedal strokes (Bini & Priego-Quesada, 2022; Fonda et al., 2014; Holliday et al., 2017). Standardised measurements in centimetres (cm) were taken from a steel-constructed sit-and-reach box and trunk and hamstring flexibility tester (Australian Medical Supplies Co., Australia). The zero position was marked on the box, which identified the starting position. Cyclists were instructed to put their right hand over their left and push the reach indicator as far as possible. Measurements were recorded if cyclists could maintain this maximum reach distance for 3 seconds.

On-bike rolling seated maximum 6-s sprint test

Cyclists placed their track bikes (Avanti Bicycle Co.) with 165 cm crank lengths and 84-inch gear on a LeMond Revolution cycle ergometer (LeMond Bicycle Inc.). Cyclists performed a slow rolling start, maintaining a cadence of approximately 20–40 rpm for four pedal revolutions. Following this, the researcher initiated the 6-second sprint effort through verbal countdown ('3–2-1-go'), with cyclists accelerating as fast as possible for the maximal sprint effort. This protocol was familiar to all participants and was applied consistently across trials (Table 2). Participants were required to stay seated and maintain their self-directed on-bike racing position. All on-bike data were collected through an SRM Science track power metre (SRM GmbH Co., Jülich, Germany) using the strain gauge and cadence sensor to calculate the torque and angular velocity of the cranks (Gardner et al., 2004; Novak et al., 2015). Raw SRM data were collected using CLogdisplay sampling at 256 Hz and processed using a bespoke MATLAB code to extract power, torque, and cadence per half-crank cycle. The highest average power output calculated over any half-crank cycle, referred to as peak power output (PPO), was the main performance metric for this benchmark test.

3-s bilateral on-bike isometrics at a 90° crank angle

Cyclists placed their track bikes on a custom-built isometric cycle ergometer to assess on-bike isometrics at a 90° crank angle (Table 2). This crank angle was selected given its reported use in elite cyclists (Kordi et al., 2020) and peak torque production typically occurs during the downstroke phase, particularly between crank angles of 45° and 135° (Bertucci et al., 2005; Dorel et al., 2005; Kordi et al., 2020). Markers were placed on bony landmarks to allow for the accurate measurement of the elbow and knee angles during testing position and complement the goniometer measurements. Cyclists were asked to push with their front leg and pull with their back leg as hard as possible, as they would when cycling on the bike, staying seated and maintaining their self-directed on-bike racing position. Torque refers to the measurement of force applied on the pedal multiplied by the crank radius (Imbery et al., 2022). In our case, the SRM measured the net effective force measured by the strain spiders within the cranks, and the maximum net torque (Nm) was extracted through a bespoke MATLAB code. Cyclists always started the testing with their preferred starting leg for team sprint, which was the left side for 85% of the cohort.

3-s prone bench pull isometrics

The elbow angles of each cyclist were matched to their individual on-bike isometric positions (Table 2). Goniometer measurements ranged from 80° to 120° elbow flexion across cyclists. Wrists were maintained in a neutral position while gripping the bench pull handlebar. A wireless load cell (MT501 Meltrons Load Cell) sampling at 520 Hz, connected via Bluetooth to an Android tablet (Galaxy Tablet Active 2 version 8.1.0) was anchored to the floor and bench pull handlebars. Cyclists were instructed to pull as hard as possible with both arms. The bench and floor anchor were placed in the same position every time, and cyclists had to maintain a straight spine by not arching their backs. Maximum force (N) was used as the primary outcome for this test.

3-s lumbar extension isometrics

A modified version (Dedering et al., 1999) of the conventional Sorenson test (Demoulin et al., 2006) was implemented and selected to more closely represent lumbar-pelvic angles of cyclists on the bike (Table 2). Cyclists wore a thoracic weight loading vest (Kensui Co., Wyoming, USA) attached to the wireless load cell (MT501 Meltrons Load Cell), which was anchored to the floor. Cyclists were instructed to cross their arms over their chest and pull upwards towards the ceiling as hard as possible using their posterior chain. The maximum instantaneous isometric force (N) was extracted.

3-s seated off-bike isometric test

A position like the on-bike isometric test was used (Table 2). Cyclists had three marked touchpoints according to track bike positions: one on an adjustable plinth to mark the seating position, one on a force plate (ForceDecks Lite V2 dual-force plates, VALD Brisbane, Australia) to mark their front foot position, and one on the floor to mark their back foot position. The markers for the feet represented the cleats of the bike pedals, with the same width (16 cm) and distance (33 cm) between markers as those measured on a bike with a 165 cm crank length. Cyclists were instructed to hold the handlebars anchored to the ground via a load cell (MT501 Meltrons Load Cell) and asked to replicate their seated race position. The researcher adjusted the plinth to mimic the same angles for the knee and elbow as for the on-bike isometrics measured using a goniometer. The force plate was zeroed per manufacturer instructions before data collection for each leg. Cyclists were asked to push down on the force plate with their forefoot, balance their back leg on the floor, and pull with the handlebars while maintaining their three touch points and knee and elbow angles. Force data from the front foot were collected using the ForceDecks, which have been demonstrated as a reliable and valid method to measure ground reaction forces (Collings et al., 2024). The data were recorded at 1000 Hz via a laptop (Hewlett-Packard Z book, 12th Generation, HP Inc.). Peak forces from both devices were combined to extract the maximum peak push-and-pull force (N) for each repetition.

Modified plank endurance test

Cyclists wore a laser light mounted on their sprint helmet to monitor head movement (Table 2), similar to the approach used in measuring the joint position error at the neck (Abdelkader et al., 2020; Treleaven et al., 2003). Cyclists were instructed to maintain a neutral prone plank position as long as possible, with only their forearms and toes in contact with a yoga mat (Bohannon et al., 2018). Their shoulders needed to be over their 90° bent elbows, and the head position needed to mimic their on-bike race position. Cyclists were positioned 90 cm away from a vertical target placed on the wall ahead of them (Table 2) and asked to point the laser in the middle of the target (green area). Maximum hold time (in seconds) was captured using a stopwatch. The test was terminated when cyclists voluntarily stopped or after the researcher provided three warnings related to the form. These warnings included loss of neutral positioning of the prone plank as described elsewhere (Bohannon et al., 2018) or when the laser moved out of the green or yellow area. This area was defined as the acceptable margin of error indicative of a 7 cm radius or 4.5° away from the centre of the target, as reported in previous research (Abdelkader et al., 2020; AlDahas et al., 2024; Kristjansson & Treleaven, 2009).

Inertial load cycle ergometer test

Cyclists completed a self-directed 5-minute warm-up on their own track bikes before mounting a custom built inertial ergometer. Briefly, wearing their own cycling shoes and similar seat geometry as their track bikes, cyclists were instructed to start accelerating as fast as possible from a static start, using their preferred start leg for the team sprint event. Cyclists had to stay seated for the maximum efforts and had a 5-minute passive rest between the three repetitions (Table 2). An inertial load ergometer was connected via Bluetooth to an Android tablet (Galaxy Tablet Active 2 version 8.1.0). Data extraction was performed through a bespoke algorithm and MATLAB code using samples of at least 60 rpm for eight complete crank revolutions. Data displayed included peak cadence (rpm), peak torque (Nm), and power (W) for every half crank revolution. The highest average power output calculated over any half-crank cycle, referred to as peak power output (PPO), was our main performance metric for this benchmark test (Table 1).

Statistical analysis

The sample size was reduced for four of the benchmark tests as one cyclist sustained an injury between day one and two, limiting completion of the sit-and-reach and on-bike benchmark tests for day two. One para cyclist could not complete the off-bike pulling benchmark tests due to an upper body disability. Two cyclists were reluctant to perform a maximum pull on day two of the lumbar extension test, due to stiffness in their lower back. Consequently, these tests were deemed unreliable, and their data were excluded from the analyses. An extreme studentised deviation (Grubb's test; α = 0.05) on all tests identified one outlier in the bench pull and modified plank test. These two data points were removed from analysis. All data were assessed for normality of distribution using the Shapiro–Wilk test (α = 0.05), and data passed assumptions of normality, except for the seated off-bike isometrics with left foot forward ($p = 0.035$).

Data were summarised using means and standard deviations (mean ± SD). For all benchmark tests, the maximal value of any one repetition performed was used for analyses because these are deemed more reliable in scientific studies (AlDahas et al., 2024) and reflective of high-performance sports. To determine the reliability of the seven benchmark tests in our elite sprint track cyclists, two-way mixed effects single measurement ICC ($ICC_{3,1}$) and typical error expressed as a coefficient of variation (CV) with 95% confidence interval [lower, upper] were computed using a statistical spreadsheet to assess the relative and absolute agreement of measures between days, respectively (Hopkins, 2015). Typical thresholds for ICC values of <0.50, from 0.50 to <0.75, from 0.75 to <0.90, and ≥0.90 were interpreted as *poor*, *moderate*, *good*, and *excellent* agreement, respectively (Koo & Li, 2016; Portney, 2020). To calculate the CV, the typical error ($TE = \frac{SDbetween-daydifference}{\sqrt{2}}$), was divided by the mean of scores from both days and expressed as a percentage. The CV is a standardised metric to identify repeatability and reproducibility (Harry et al., 2024; Hopkins, 2004). A test–retest CV of 10% or less may be deemed *acceptable* (Atkinson & Nevill, 1998); however, in power athletes, a smaller CV is desired to optimise performance measurement (Harry et al., 2024), as illustrated with performance-related tests in power athletes with a CV below 5% (Hopkins et al., 2001). Furthermore, a two-tailed paired *t*-test was performed to identify significant systematic bias between days. Finally, distribution-based methods were used to calculate the minimal clinically important differences (MCID) for each measure as 1.96 of the typical error, representing the 95% confidence interval margin of error (Franceschini et al., 2023).

To assess the relationship between our performance outcome (i.e., PPO from the maximum seated inertial load cycle ergometer test) and the benchmark tests, Pearson's correlations with 95% confidence intervals and associated *p*-values were calculated using the data from day one benchmark tests given the larger sample size. Thresholds for Pearson's *r* values were categorised as *poor* (<0.50), *moderate* (0.50 to <0.75), *good* (0.75 to <0.90), and *excellent* (≥0.90) relationships when statistically significant (Dancey & Reidy, 2004). Correlations were deemed *perfect* when *r* values equalled 1.00. To control for Type I error due to multiple comparisons, a Bonferroni correction was applied (Haynes, 2013). Nine benchmark metrics were evaluated, including a bilateral isometric strength test. The conventional alpha level of 0.05 was divided by 9, resulting in an adjusted significance threshold of $p \leq 0.005$. This conservative correction reduces the error rate to 5%, which would otherwise inflate to approximately 37% without adjustment (Sainani & Chamari, 2022).

Analysis was performed using Microsoft® Excel® (Office 365 M) and GraphPad Prism (10.3.1). A correlation matrix was used to analyse the interchangeability between using isometrics on and off the bike and seated dynamic cycling.

Table 3. Mean ± standard deviation values from the benchmark tests performed on day 1 and day 2 by the 19 elite track cyclists. Test–retest statistics with 95% confidence intervals [lower, upper] are reported, and include the between-day typical error expressed as a coefficient of variation, intraclass correlation coefficient, paired *t*-test p-value, and minimal clinically important difference.

		Descriptive		Statistics			
Benchmark tests	Cyclists	Day 1	Day 2	CV (%)	ICC [95%]	*P* value	MCID
Modified sit-and-reach (cm)	19	47.6 ± 5.3	48.0 ± 5.6	2.0 [1.5, 3.0]	0.97 [0.93, 0.99]	.240	1.9 [1.4, 2.8]
On-bike rolling seated max sprints – PPO (W)	19	1240.3 ± 317.0	1233.7 ± 316.2	2.8 [2.1, 4.2]	0.99 [0.97, 1.0]	.561	34.7 [26.2, 51.4]
On-bike isometrics at 90° – L foot forward (Nm)	19	273.1 ± 47.2	268.4 ± 57.1	5.5 [4.1, 8.1]	0.93 [0.82, 0.97]	.343	29.1 [22, 43.0]
On-bike isometrics at 90° –R foot forward (Nm)	19	261.4 ± 48.7	261.2 ± 53.9	4.2 [3.2, 6.2]	0.96 [0.90, 0.98]	.960	21.4 [16.2, 31.7]
Bench pull isometrics (N)[†]	16	1231.4 ± 278.2	1222.9 ± 262.2	4.7 [3.4, 7.2]	0.96 [0.90, 0.99]	.681	112.2 [82.9, 173.7]
Lumbar extension isometrics (N)[†]	16	822.2 ± 144.3	1001.0 ± 130.5	3.8 [2.8, 5.9]	0.93 [0.82,0.98]	.282	74.3 [54.9, 115.0]
Seated off-bike isometrics – L foot forward (N)[†]	17	1474.7 ± 251.0	1527.8 ± 243.8	5.2 [3.8, 7.9]	0.92 [0.78, 0.97]	.063	151.9 [113.1, 231.2]
Seated off-bike isometrics – R foot forward (N)[†]	17	1527.0 ± 232.9	1568.8 ± 206.3	4.2 [3.2, 6.5]	0.92 [0.80, 0.97]	.083	128.9 [96.0, 196.2]
Modified plank test (s)[†]	17	93.4 ± 37.7	97.8 ± 38.0	9.6 [7.1, 14.5]	0.95 [0.87, 0.98]	.178	17.9 [13.3, 27.2]

[†]Missing data as indicated by the number of cyclists.
Abbreviations: CV, coefficient of variation; ICC, intraclass correlation; L, left; MCID, minimal clinically important difference; PPO, peak power output; R, right; SD, standard deviation.

Results

All seven benchmark tests delivered reliable performance metrics between the two testing days (Table 3). The consistency of the measurements was *excellent* with ICC values (0.92 – 0.99), with lower confidence limits spanning the *good*-to-*excellent* range (0.78 – 0.97). All performance tests showed *acceptable* reliability for high performance sports settings with CVs < 5% between test days, except for two results: seated off-bike isometrics (left foot forward, 5.2%) and the modified plank test (9.6%). All benchmark tests showed no significant systematic bias between days (paired *t*-test $p \geq 0.063$). Descriptive data specific to the subgroups of cyclists participating are provided in supplementary material (supplementary material S1).

All benchmark tests showed *moderate* to *excellent* ($r = 0.52$–0.94) correlations with PPO from the maximum seated inertial load cycle ergometer test, which was our main sprint cycling performance outcome, except for the modified sit-and-reach and the modified plank tests (Table 4). After applying a Bonferroni correction (adjusted significance threshold $p \leq 0.005$), no statistically significant correlations were observed between the performance outcome and the STR, modified lumbar extension isometrics, or modified plank endurance test. Table 5 demonstrates statistically significant (all $p \leq 0.001$) *moderate* to *good* correlation between seated on- and off-bike isometrics ($r \geq 0.73$) and on- and off-bike isometrics and the PPO during on-bike rolling seated max sprints ($r \geq 0.77$), supporting relative test interchangeability.

Table 4. Relationship between the performance marker (peak power output from the maximum seated inertial load cycle ergometer test) and maximum value recorded for each benchmark test during day one from 19 elite track cyclists. Data presented are Pearson's correlations (*r)* with 95% confidence intervals [lower, upper] and associated *p* values.

Benchmark tests	Cyclists	Pearson r	Magnitude†	P value
Modified sit-and-reach (cm)	19	−0.41 [−0.73, 0.05]	NA	.077
On-bike rolling seated max sprints – PPO (W)	19	0.94 [0.82, 0.97]	*Large*	<.001*
On-bike isometrics at 90° – L foot forward (Nm)	19	0.80 [0.54, 0.92]	*Large*	<.001*
On-bike isometrics at 90° –R foot forward (Nm)	19	0.71 [0.38, 0.88]	*Large*	.001*
Bench pull isometrics (N)‡	18	0.85 [0.64, 0.94]	*Large*	<.001*
Lumbar extension isometrics (N)	19	0.52 [0.09, 0.79]	*Large*	.023
Seated off-bike isometrics – L foot forward (N)‡	18	0.69 [0.33, 0.87]	*Large*	.002*
Seated off-bike isometrics – R foot forward (N)‡	18	0.71 [0.36, 0.88]	*Large*	.001*
Modified plank test (s)	19	−0.18 [−0.59, 0.29]	NA	.449

Notes. *Statistically significant correlation (Bonferroni corrected $p \leq 0.005$). †Magnitudes of correlations considered *small*, *medium*, and *large* when reaching 0.10, 0.30, and 0.50, respectively. ‡Missing data as indicated by the number of cyclists. Abbreviations: L, left; PPO, peak power output; R, right. 85% of cyclists used their left leg as their preferred start leg during the team sprint event.

Discussion

The test–retest reliability of the assessed benchmark tests in our elite track cyclist cohort was excellent, with ICC values ranging from 0.92 to 0.99, though confidence intervals varied due to the modest sample size. Correlation coefficients were ≤5% for the maximum force production benchmark tests, suggesting high precision and reliability within power athletes (Harry et al., 2024; Hopkins et al., 2001). In addition, many of the isometric tests were completed at angles matching the on-bike posture of the sprint cyclists, increasing their ecological validity and relevance to the sport. While adjusting the elbow angle to match individual cycling positions improved ecological validity, the force output in the isometric bench pull is angle dependent and performing the test at 80° or 120° of elbow flexion would likely produce different results (Lum & Aziz, 2020). Therefore, this reduces the applicability of our findings as a generalised benchmark reference.

The modified plank isometric test is classified as an endurance test and exhibited the least favourable CV between days at 9.6%. However, isometric endurance tests are more unreliable, with greater variability in performance linked to motivation, fitness levels, and discomfort (Janik et al., 2021). Nonetheless, the CV was still under 10%, which is deemed excellent test–retest reproducibility for endurance isometric testing (Janik et al., 2021) and within the normal ranges (10–15%) for reproducibility in biological systems (Stokes, 1985).

Assessing the reliability of benchmark tests with populations of interests is essential since, without reliability, these tests cannot be considered valid (Weakley et al., 2024). Furthermore, in high performance sports, benchmark tests reflective of performance are important to inform exercise prescription, identify talent, and monitor athletes. Previous data have shown a strong correlation between peak force from an isometric mid-thigh pull (IMTP) and cycling performances, specifically in relation to peak power during a cycling Wingate test ($r = 0.740$, $p < 0.05$) and track cycling split times ($r = -0.490$ to -0.550, $p < 0.05$) (Stone et al., 2004). Although IMTP force can be directly related to cycling performance (Lum et al., 2020), to our knowledge, strong correlations have not been established for other isometric benchmark tests now commonly used in elite track

Table 5. Correlation matrix: Pearson correlation and 95% confidence intervals between seated on and off-bike isometrics (nm) and ppo during on-bike rolling seated max sprints (w).

	On-bike isometrics at 90° L foot forward (Nm)	On-bike isometrics at 90° R foot forward (Nm)	On-bike rolling seated max sprints PPO (W)	Seated off-bike isometrics L foot forward (Nm)‡	Seated off-bike isometrics R foot forward (Nm)‡
On-bike isometrics at 90° L foot forward (Nm)		0.88 [0.71, 0.95]	0.87 [0.69, 0.95]	0.78 [0.50, 0.92]	0.76 [0.45, 0.91]
On-bike isometrics at 90° R foot forward (Nm)	0.88 [0.71, 0.95]		0.84 [0.63, 0.94]	0.71 [0.36, 0.88]	0.73 [0.39, 0.89]
On-bike rolling seated max sprints – PPO (W)	0.87 [0.69, 0.95]	0.84 [0.63, 0.94]		0.78 [0.49, 0.91]	0.77 [0.48, 0.91]
Seated off-bike isometrics L foot forward (Nm)‡	0.78 [0.50, 0.92]	0.71 [0.36, 0.88]	0.78 [0.49, 0.91]		0.93 [0.83, 0.98]
Seated off-bike isometrics R foot forward (Nm)‡	0.76 [0.45, 0.91]	0.73 [0.39, 0.89]	0.77 [0.48, 0.91]	0.93 [0.83, 0.98]	

Pearson correlation: ■ = perfect correlation; ▨ = excellent correlation; □ = good correlation.
Abbreviations: L, left; PPO, peak power output; R, right. 85% of cyclists used their left leg as their preferred start leg during the team sprint event.

cyclists. Our results indicated *moderate* to *excellent* positive relationship between the performance metric of the benchmark tests and the ability to produce power ($r = 0.52$ to 0.94, $p \leq 0.02$), except for flexibility sit-and-reach ($r = -0.41$, $p = 0.08$) and modified plank endurance tests ($r = -0.18$, $p = 0.45$).

Previous research has correlated ergometer PPO of sprint cyclists to sprint track cycling performances (Gardner et al., 2007; Kordi et al., 2019; Martin et al., 1997). A comparison between maximum inertial load cycle ergometer and maximum standing start 65 m field-base testing indicated no statistically significant differences between the PPO ($p = 0.984$), maximum torque ($p = 0.840$) and optimal pedalling rate ($p = 0.863$) of these two tasks (Gardner et al., 2007). Furthermore, a good linear fit between maximum torque-pedalling rate on an inertial load cycle ergometer ($r^2 = 0.990$) and on the track ($r^2 = 0.983$) has been established (Gardner et al., 2007). The custom-built inertial load cycle ergometer was set as the main sprint cycling specific performance metric in our study, given the reliable method to assess maximum power output (Gardner et al., 2007; Martin et al., 1997; Wickwire et al., 2011). However, the inertial load cycle ergometer is not always accessible for use as a performance metric, indicating a limitation of this study. Our data indicate that a normal ergometer may be an adequate substitute given the excellent relationship identified between the PPO from the inertial ergometer and seated on-bike maximum 6 s sprint on the standard ergometer ($r = 0.94$). Our benchmark tests may help understand the physical qualities of cyclists in an elite setting, potentially leading to improved monitoring and training (Weakley et al., 2024), given their excellent reliability and *good* to *excellent* relationship to a key performance indicator.

Although the modified sit-and-reach flexibility test ($r = -0.41$) and modified plank endurance test ($r = -0.18$) were not hypothesised to correlate strongly with the performance metric, their inclusion in the correlation analysis was intentional. This allowed the exploration of whether commonly used benchmark tools in cycling might hold relevance to performance in elite sprint cyclists, and ascertain the reliability for use in injury assessment and monitoring. Time-loss injuries negatively impact performance (Raysmith & Drew, 2016), and lower back injuries are reported as one of the highest burdens in sprint track cycling (Palmer-Green et al., 2014). Our modified sit-and-reach test showed excellent reliability and reflects the flexibility of the trunk and hamstring flexibility in the sagittal plane. In cyclists, too much or too little mobility in the spine may be detrimental. For instance, increased spine mobility in the sagittal and frontal planes has been associated with increased pain in young adults (Perez de la Cruz, 2024), while increased spine flexion has been linked to non-specific lumbar pain in cyclists (Van Hoof et al., 2015). In contrast, decreased lumbar mobility in the sagittal plane has been associated with lumbar pain in adults (Jones et al., 2005; Vatovec & Voglar, 2024). Furthermore, monitoring hamstring flexibility in cyclists may prove beneficial, since reduced hamstring flexibility can negatively influence aerodynamics (Holliday & Swart, 2021) and trunk endurance strength (Kapre & Alexander, 2024). The modified sit-and-reach test could be used to monitor cyclists' mobility longitudinally. However, further research is required to determine the value of these two benchmark tests in injury management or risk determination.

Optimal performance is achieved by maintaining an equilibrium between resistance (i.e., air or drag, rolling or frictional) and propulsive power on the track (Douglas et al., 2021). The modified plank endurance test did not show a significant correlation with our performance metric, maximum power output. This test included a self-directed head position aimed at reducing the frontal surface to make it more applicable to track sprint cycling. A reduction in the frontal surface is indirectly linked to performance by reducing the coefficient of drag area (Crouch et al., 2019); however, further research is needed to confirm this relationship, indicating a limitation of this study.

On-bike isometrics are suggested to provide an appropriate training stimulus for sprint track cyclists (Kordi et al., 2020). However, having access to a custom-built ergometer and expensive SRM with analytic software to extract peak force from track bikes may not always be feasible. Our study identified a *moderate* to *good* correlation between seated on- and off-bike isometrics (right foot, $r = 0.73$; left foot, $r = 0.78$), making them interchangeable as benchmark tests, pending the equipment at hand. The off-bike isometric benchmark test was designed to replicate key biomechanical features of the on-bike positioning. Recognising the reduced ecological validity due to the absence of dynamic pedalling, this approach aligns with previous research supporting joint-specific isometric testing in this sport-specific context (Kordi et al., 2020; Lewandowski & McMullan, 2023). Force platforms are relatively accessible in performance gyms and physiotherapy practices (Vald, 2025), and may be suitable to use for training and assessments in the absence of a custom-built ergometer. Our study also identified a *good* correlation between on-bike isometrics and maximum 6-second seated sprint cycling on a track bike (left foot, $r = 0.87$; right foot, $r = 0.84$). This supports the monitoring of benchmark tests when an inertial load cycle ergometer or force platform is not available. While high intercorrelations ($r \geq 0.73$) between benchmark tests support interchangeability, they may also indicate redundancy, suggesting that a reduced test battery could still provide sufficient insight into key performance characteristics.

This study has limitations, particularly the small sample size of nineteen elite track sprint cyclists, with a further reduction to 16 during the bench pull benchmark. Access to large sample sizes in highly specific elite cohorts is inherently challenging and has been widely acknowledged in the literature (Skorski & Hecksteden, 2021). Our study aligns with previous investigations involving similarly small samples in elite track sprint cycling (Kordi & van Rijswijk, 2024; Kordi et al., 2020, 2022). The elite athlete population is, by nature, limited, making large-scale recruitment impractical (Skorski & Hecksteden, 2021). This study provides practical relevance through rigorous standardisation protocols on a sample size presenting over 90% of the national population in elite track sprint cyclists, including Olympians. Furthermore, the confidence intervals of reliability indicating *good* reliability at worst (ICC ≥ 0.78). Nonetheless, we acknowledge that the reduced sample size may limit statistical power and precision when attempting to generalise findings beyond this population.

Our choice of 90° crank angle was informed by prior research indicating that peak torque production typically occurs during the downstroke phase, particularly between crank angles of 45° and 135° (Bertucci et al., 2005; Dorel et al., 2005; Kordi et al., 2020). While this may not reflect the entire torque profile, it provides a biomechanically relevant and standardised position for assessing maximal force output—a major contributing factor to performance in track sprint cycling (Douglas et al., 2021).

The off-bike isometric benchmark test was designed to replicate key biomechanical features of the on-bike positioning. Recognising the reduced ecological validity due to the absence of dynamic pedalling, this approach aligns with previous research supporting joint-specific isometric testing in a sport-specific context (Kordi et al., 2020; Lewandowski & McMullan, 2023).

Medal outcome sensitivity in elite cycling can occur with race time changes as small as 0.5–1.5% (Paton & Hopkins, 2006). Our study focused on benchmark predictors, such as isometric strength, rather than direct race performance metrics, which inherently exhibit higher variability (Hopkins et al., 2001; Weakley et al., 2024). While we reported statistical significance and calculated MCID using distribution-based methods (Franceschini et al., 2023), we acknowledge that practical significance in terms of race outcome prediction remains beyond the scope of this study. Although the same researcher administered all tests, which were familiar to most athletes, inter-rater reliability was not formally assessed, and practical limitations may arise in specific tests due to fear of injury or discomfort, as experienced with the lumbar extension isometric hold in our study.

Cyclists maintain different training sessions between the testing days within this elite setting. Therefore, we could not control for fatigue or other variables influencing the results for each individual. The environmental reproducibility was not of a laboratory standard; however, tests occurred in the same temperature-controlled physiotherapy clinic and gym. Access to different equipment may be challenging for some practitioners, such as the inertial load cycle ergometer, force platforms or SRM; however, we tried to provide options for interchangeability.

Conclusion

We have established the reliability of benchmark tests, mainly isometrics, used with elite track sprint cyclists. Six of the nine benchmark metrics, including bilateral isometric measures, demonstrated strong and statistically significant relationships with the performance metric, peak power output. Additionally, these tests pose fewer injury risks in an elite setting as maximum isometric force causes less fatigue compared to dynamic force. This study is a novel study providing information on elite cyclists and opens avenues for exploring further research to examine the relationships between isometric benchmark tests and different performance metrics within elite track sprint cyclists.

Acknowledgments

The authors would like to thank the support from Cycling New Zealand and all cyclists participating in this study.

Disclosure statement

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

Funding

Prime Minister Scholarship and High Performance Sport New Zealand supported Roné Thompson in completing this study.

ORCID

Roné Thompson http://orcid.org/0009-0006-4292-1125
Carl Paton http://orcid.org/0000-0002-7418-7213
Rodrigo Rico Bini http://orcid.org/0000-0002-2138-7350
Kim Hébert-Losier http://orcid.org/0000-0003-1087-4986

References

Abdelkader, N. A., Mahmoud, A. Y., Fayaz, N. A., & Mahmoud, L. S. (2020). Decreased neck proprioception and postural stability after induced cervical flexor muscles fatigue. *Journal of Musculoskeletal and Neuronal Interactions*, *20*(3), 421–428.

AlDahas, A., Devecchi, V., Deane, J. A., & Falla, D. (2024). Responsiveness of the cervical joint position error test to detect changes in neck proprioception following four weeks of home-based proprioceptive training. *PLOS ONE*, *19*(5), e0303066. https://doi.org/10.1371/journal.pone.0303066

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*, *26*(4), 217–238. https://doi.org/10.2165/00007256-199826040-00002

Bahr, R. (2016). Why screening tests to predict injury do not work-and probably never will.: A critical review. *British Journal of Sports Medicine*, *50*(13), 776–780. https://doi.org/10.1136/bjsports-2016-096256

Behm, D. G., & Sale, D. G. (1993). Intended rather than actual movement velocity determines velocity-specific training response. *Journal of Applied Physiology*, *74*(1), 359–368. https://doi.org/10.1152/jappl.1993.74.1.359

Bertucci, W., Grappe, F., Girard, A., Betik, A., & Rouillon, J. D. (2005). Effects on the crank torque profile when changing pedalling cadence in level ground and uphill road cycling. *Journal of Biomechanics*, *38*(5), 1003–1010. https://doi.org/10.1016/j.jbiomech.2004.05.037

Bini, R., & Priego-Quesada, J. (2022). Methods to determine saddle height in cycling and implications of changes in saddle height in performance and injury risk: A systematic review. *Journal of Sports Sciences*, *40*(4), 386–400. https://doi.org/10.1080/02640414.2021.1994727

Bohannon, R. W., Steffl, M., Glenney, S. S., Green, M., Cashwell, L., Prajerova, K., & Bunn, J. (2018). The prone bridge test: Performance, validity, and reliability among older and younger adults. *Journal of Bodywork and Movement Therapies*, *22*(2), 385–389. https://doi.org/10.1016/j.jbmt.2017.07.005

Borg, D. N., Bach, A. J. E., O'Brien, J. L., & Sainani, K. L. (2022). Calculating sample size for reliability studies. *PM & R*, *14*(8), 1018–1025. https://doi.org/10.1002/pmrj.12850

Chandran, A., Nedimyer, A. K., Register-Mihalik, J. K., DiPietro, L., & Kerr, Z. Y. (2019). Comment on: "Incidence, severity, aetiology and prevention of sports injuries: A review of concepts". *Sports Medicine*, *49*(10), 1621–1623. https://doi.org/10.1007/s40279-019-01154-1

Collings, T. J., Lima, Y. L., Dutaillis, B., & Bourne, M. N. (2024). Concurrent validity and test-retest reliability of VALD ForceDecks' strength, balance, and movement assessment tests. *Journal of Science & Medicine in Sport*, *27*(8), 572–580. https://doi.org/10.1016/j.jsams.2024.04.014

Craig, N. P., & Norton, K. I. (2001). Characteristics of track cycling. *Sports Medicine*, *31*(7), 457–468. https://doi.org/10.2165/00007256-200131070-00001

Crouch, T., Menaspà, P., Barry, N., Brown, N., Thompson, M. C., & Burton, D. (2019). A wind-tunnel case study: Increasing road cycling velocity by adopting an aerodynamically improved sprint position. *Journal of Sports Engineering and Technology*, *235*(4), 301–309. https://doi.org/10.1177/1754337119866962

Dancey, C. P., & Reidy, J. (2004). *Statistics without maths for psychology*. Prentice Hall.

Dedering, A., Németh, G., & Harms-Ringdahl, K. (1999). Correlation between electromyographic spectral changes and subjective assessment of lumbar muscle fatigue in subjects without pain from the lower back. *Clinical Biomechanics*, *14*(2), 103–111. https://doi.org/10.1016/S0268-0033(98)00053-9

Demoulin, C., Vanderthommen, M., Duysens, C., & Crielaard, J. M. (2006). Spinal muscle evaluation using the Sorensen test: A critical appraisal of the literature. *Joint Bone Spine*, *73* (1), 43–50. https://doi.org/10.1016/j.jbspin.2004.08.002

DiDomenico, F., & Raiola, G. (2021). Effects of training fatigue on performance. *Journal of Human Sport & Exercise*, *16*. https://doi.org/10.14198/jhse.2021.16.Proc2.63

Dorel, S., Hautier, C. A., Rambaud, O., Rouffet, D., Van Praagh, E., Lacour, J. R., & Bourdin, M. (2005). Torque and power-velocity relationships in cycling: Relevance to track sprint performance in world-class cyclists. *International Journal of Sports Medicin*, *26*(9), 739–746. https://doi.org/10.1055/s-2004-830493

Douglas, J., Ross, A., & Martin, J. C. (2021). Maximal muscular power: Lessons from sprint cycling. *Sports Medicone Open*, *7*(1), 48. https://doi.org/10.1186/s40798-021-00341-7

Folland, J. P., Hawker, K., Leach, B., Little, T., & Jones, D. A. (2005). Strength training: Isometric training at a range of joint angles versus dynamic training. *Journal of Sports Science*, *23*(8), 817–824. https://doi.org/10.1080/02640410400021783

Fonda, B., Sarabon, N., & Li, F. X. (2014). Validity and reliability of different kinematics methods used for bike fitting. *Journal of Sports Sciences*, *32*(10), 940–946. https://doi.org/10.1080/02640414.2013.868919

Franceschini, M., Boffa, A., Pignotti, E., Andriolo, L., Zaffagnini, S., & Filardo, G. (2023). The minimal clinically important difference changes greatly based on the different calculation methods. *American Journal of Sports Medicine*, *51*(4), 1067–1073. https://doi.org/10.1177/03635465231152484

Gardner, A. S., Martin, J. C., Martin, D. T., Barras, M., & Jenkins, D. G. (2007). Maximal torque- and power-pedaling rate relationships for elite sprint cyclists in laboratory and field tests. *European Journal Applied Physiology*, *101*(3), 287–292. https://doi.org/10.1007/s00421-007-0498-4

Gardner, A., Stephens, S., Martin, D. T., Lawton, E., Lee, H., & Jenkins, D. (2004). Accuracy of SRM and power tap power monitoring systems for bicycling. *Medicine & Science in Sports & Exercise*, *36*(7), 1252–1258. https://doi.org/10.1249/01.mss.0000132380.21785.03

Grgic, J., Scapec, B., Mikulic, P., & Pedisic, Z. (2022). Test-retest reliability of isometric mid-thigh pull maximum strength assessment: A systematic review. *Biol Sport*, *39*(2), 407–414. https://doi.org/10.5114/biolsport.2022.106149

Grover, Z., McCormack, J., Cooper, J., & Fisher, J. P. (2024). Test-retest reliability of a single isometric mid-thigh pull protocol to assess peak force and strength-endurance. *PeerJ*, 12. https://doi.org/10.7717/peerj.17951

Harry, J. R., Hurwitz, J., Agnew, C., & Bishop, C. (2024). Statistical tests for sports science practitioners: Identifying performance gains in individual athletes. *Journal of Strength and Conditioning Research*, *38*(5), e264–e272. https://doi.org/10.1519/jsc.0000000000004727

Haynes, W. (2013). Bonferroni correction. In W. Dubitzky, O. Wolkenhauer, K. H. Cho, & H. Yokota (Eds.), *Encyclopedia of systems biology* (pp. 154–154). Springer New York. https://doi.org/10.1007/978-1-4419-9863-7_1213

Holliday, W., Fisher, J., Theo, R., & Swart, J. (2017). Static versus dynamic kinematics in cyclists: A comparison of goniometer, inclinometer and 3D motion capture. *European Journal of Sport Science*, *17*(9), 1129–1142. https://doi.org/10.1080/17461391.2017.1351580

Holliday, W., & Swart, J. (2021). Anthropometrics, flexibility and training history as determinants for bicycle configuration. *Sports Medicine and Health Science*, *3*(2), 93–100. https://doi.org/10.1016/j.smhs.2021.02.007

Hopkins, W. G. (2004). How to interpret changes in an athletic performance test. *Sportscience*, *8*, 1–7 https://sportsci.org/jour/04/wghtests.htm

Hopkins, W. G. (2015). Spreadsheets for analysis of validity and reliability. *Sportscience*, *19*, 36–44. https://sportsci.org/2015/ValidRely.htm

Hopkins, W. G., Schabort, E. J., & Hawley, J. A. (2001). Reliability of power in physical performance tests. *Sports Medicine*, *31*(3), 211–234. https://doi.org/10.2165/00007256-200131030-00005

Imbery, F., Leo, P., Wakefield, J., & Schoberer, U. (2022). Torque behaviour during cycling sprints from different pedalling frequencies. *Journal of Science and Cycling*, *11*(2), 1–7.

James, L. P., Weakley, J., Comfort, P., & Huynh, M. (2023). The relationship between isometric and dynamic strength following resistance training: A systematic review, meta-analysis, and level of agreement. *International Journal of Sports Physiology and Performance*, *19*(1), 2–12. https://doi.org/10.1123/ijspp.2023-0066

Janik, F., Toulotte, C., Seichepine, A. L., Masquelier, B., Barbier, F., & Fabre, C. (2021). Isometric strength database for muscle maximal voluntary endurance field tests: Normative data. *Sports Medicine*, *7*(1), 47. https://doi.org/10.1186/s40798-021-00338-2

Jones, M. A., Stratton, G., Reilly, T., & Unnithan, V. B. (2005). Biological risk indicators for recurrent non-specific low back pain in adolescents. *British Journal of Sports Medicine*, *39*(3), 137–140. https://doi.org/10.1136/bjsm.2003.009951

Kapre, T. M. S., & Alexander, J. O. R. (2024). A correlation study of weak core muscles with hamstring muscles flexibility in young adults. *Bulletin of Faculty of Physical Therapy*, *29*(1). https://doi.org/10.1186/s43161-024-00244-0

Kellmann, M., Bertollo, M., Bosquet, L., Brink, M., Coutts, A. J., Duffield, R., Erlacher, D., Halson, S. L., Hecksteden, A., Heidari, J., Kallus, K. W., Meeusen, R., Mujika, I., Robazza, C., Skorski, S., Venter, R., & Beckmann, J. (2018). Recovery and performance in sport: Consensus statement. *International Journal of Sports Physiology Performance*, *13*(2), 240–245. https://doi.org/10.1123/ijspp.2017-0759

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Kordi, M., Evans, M., & Howatson, G. (2021). Quasi-isometric cycling: A case study investigation of a novel method to augment peak power output in sprint cycling. *International Journal of Sports Physiology Performance*, *16*(3), 452–455. https://doi.org/10.1123/ijspp.2020-0100

Kordi, M., Folland, J., Goodall, S., Barratt, P., & Howatson, G. (2019). Isovelocity vs. isoinertial sprint cycling tests for power- and torque-cadence relationships. *International Journal of Sports Medicine*, *40*(14), 897–902. https://doi.org/10.1055/a-0989-2387

Kordi, M., Folland, J. P., Goodall, S., Menzies, C., Patel, T. S., Evans, M., Thomas, K., & Howatson, G. (2020). Cycling-specific isometric resistance training improves peak power output in elite sprint cyclists. *Scandinavian Journal of Medicine and Science in Sports*, *30*(9), 1594–1604. https://doi.org/10.1111/sms.13742

Kordi, M., Galis, G., Erp, T. V., & Terra, W. (2022). Reliability and sensitivity of the Notio Konect to quantify coefficient of drag area in elite track cyclists. *European Journal of Sport Science*, *22*(6), 774–779. https://doi.org/10.1080/17461391.2021.1891296

Kordi, M., & van Rijswijk, I. (2024). Performance analysis and mechanical determinants of the opening lap of the team sprint in elite-level track cycling. *European Journal of Sport Science*, *24*(9), 1240–1246. https://doi.org/10.1002/ejsc.12158

Kristjansson, E., & Treleaven, J. (2009). Sensorimotor function and dizziness in neck pain: Implications for assessment and management. *Journal of Orthopaedic and Sports Physical Therapy*, *39*(5), 364–377. https://doi.org/10.2519/jospt.2009.2834

Kruger, R. L., Aboodarda, S. J., Jaimes, L. M., MacIntosh, B. R., Samozino, P., & Millet, G. Y. (2019). Fatigue and recovery measured with dynamic properties versus isometric force: Effects of exercise intensity. *Journal of Experimental Biology*, *222*(Pt 9). https://doi.org/10.1242/jeb.197483

Kubo, K., Ohgo, K., Takeishi, R., Yoshinaga, K., Tsunoda, N., Kanehisa, H., & Fukunaga, T. (2006). Effects of isometric training at different knee angles on the muscle-tendon complex in vivo. *Scandinavian Journal of Medicine and Science in Sports*, *16*(3), 159–167. https://doi.org/10.1111/j.1600-0838.2005.00450.x

Lewandowski, G., & McMullan, S. (2023). Relationship between isometric peak force and maximal sprinting in elite track cyclists. *Journal of Strength and Conditioning Research*, *41*(3), 215–223. https://doi.org/10.1007/s42978-023-00241-0

Lum, D., & Aziz, L. (2020). Validity and reliability of the isometric prone bench pull test. *International Journal of Sports Medicine*, *41*(8), 520–527. https://doi.org/10.1055/a-1103-2173

Lum, D., & Barbosa, T. M. (2019). Brief review: Effects of isometric strength training on strength and dynamic performance. *International Journal of Sports Medicine*, *40*(6), 363–375. https://doi.org/10.1055/a-0863-4539

Lum, D., Haff, G. G., & Barbosa, T. M. (2020). The relationship between isometric force-time characteristics and dynamic performance: A systematic review. *Sports (Basel)*, *8*(5). https://doi.org/10.3390/sports8050063

Marks, R. (1993). The effect of isometric quadriceps strength training in mid-range for osteoarthritis of the knee. *Arthritis Care and Research Journal*, *6*(1), 52–56. https://doi.org/10.1002/art.1790060110

Martin, J. C., Wagner, B. C., & Coyle, E. F. (1997). The inertial-load method determines maximal cycling power in a single exercise bout. *Medicine and Science in Sports and Exercise*, *29*(11), 1505–1512. https://doi.org/10.1097/00005768-199711000-00018

Millet, G. P., Brocherie, F., & Burtscher, J. (2021). Olympic sports science-bibliometric analysis of all Summer and Winter Olympic sports research. *Frontiers in Sports and Active Living*, *3*, 772140. https://doi.org/10.3389/fspor.2021.772140

Novak, A., Steben, C., & Dascombe, B. (2015). Agreement between LeMond revolution cycle ergometer and SRM power meter during power profile and ramp protocol assessments. *Journal of Science and Cycling*, *4*(3), 37–43.

O'Neill, S., Weeks, A., Norgaard, J. E., & Jorgensen, M. G. (2023). Validity and intrarater reliability of a novel device for assessing plantar flexor strength. *PLOS ONE*, *18*(3), e0282395. https://doi.org/10.1371/journal.pone.0282395

Palmer-Green, D., Burt, P., Jaques, R., & Hunter, G. (2014). Epidemiological study of injury in British cycling: 2011–2013. *British Journal of Sports Medicine*, *48*(7), 650. https://doi.org/10.1136/bjsports-2014-093494.239

Paton, C., & Hopkins, W. G. (2006). Variation in performance of elite cyclists from race to race. *European Journal of Sport Science*, *6*, 25–31. https://doi.org/10.1080/17461390500422796

Perez de la Cruz, S. (2024). Influence and relationship of pain on lumbar biomechanics in a young adult population with non-specific low back pain. *Sports*, *12*(7). https://doi.org/10.3390/sports12070190

Phillips, K. E., & Hopkins, W. G. (2020). Determinants of cycling performance: A review of the dimensions and features regulating performance in elite cycling competitions. *Sports Medicine Open*, *6*(1), 23. https://doi.org/10.1186/s40798-020-00252-z

Portney, L. G. (2020). *Foundation of clinical research: Applications to evidence-based practice* (4th ed.). F.A. Davis Company. https://fadavispt.mhmedical.com/content.aspx?bookid=2885&sectionid=243179474

Raysmith, B. P., & Drew, M. K. (2016). Performance success or failure is influenced by weeks lost to injury and illness in elite Australian track and field athletes: A 5-year prospective study. *Journal of Science & Medicine in Sport*, *19*(10), 778–783. https://doi.org/10.1016/j.jsams.2015.12.515

Rio, E., van Ark, M., Docking, S., Moseley, G. L., Kidgell, D., Gaida, J. E., van den Akker-Scheek, I., Zwerver, J., & Cook, J. (2017). Isometric contractions are more analgesic than isotonic contractions for patellar tendon pain: An In-Season randomized clinical trial. *Clinical Journal of Sport Medicine*, *27*(3), 253–259. https://doi.org/10.1097/jsm.0000000000000364

Ros, F. E., Vaquero-Cristóbal, R., Marfell-Jones, M., & Marfell-Jones, M. (2019). *International standards for anthropometric assessment*. International Society for the Advancement of Kinanthropometry (ISAK). https://books.google.co.nz/books?id=E4edzgEACAAJ

Sainani, K., & Chamari, K. (2022). Wish list for improving the quality of statistics in sport science. *International Journal of Sports Physiology and Performance*, *17*(5), 673–674. https://doi.org/10.1123/ijspp.2022-0023

Skorski, S., & Hecksteden, A. (2021). Coping with the "small sample-small relevant effects" dilemma in elite sport research. *International Journal of Sports Physiology and Performance*, *16*(11), 1559–1560. https://doi.org/10.1123/ijspp.2021-0467

Smajla, D., Šarabon, N., García Ramos, A., Janicijevic, D., & Kozinc, Ž. (2024). Influence of isometric and dynamic fatiguing protocols on dynamic strength index. *Applied Sciences*, *14* (7), 2722. https://doi.org/10.3390/app14072722

Stavridis, I., Zisi, M., Arsoniadis, G. G., Terzis, G., Tsolakis, C., & Paradisis, G. P. (2025). Relationship between isometric mid-thigh pull force, sprint acceleration mechanics and performance in national-level track and field athletes. *Applied Sciences*, *15*(3), 1089. https://doi.org/10.3390/app15031089

Stokes, M. (1985). Reliability and repeatability of methods for measuring muscle in physiotherapy. *Physiotherapy Practice*, *1*(2), 71–76. https://doi.org/10.3109/09593988509163853

Stone, M. H., Sands, W. A., Carlock, J., Callan, S., Dickie, D., Daigle, K., Cotton, J., Smith, S. L., & Hartman, M. (2004). The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *Journal of Strength and Conditioning Research*, *18*(4), 878–884. https://doi.org/10.1519/00124278-200411000-00034

Treleaven, J., Jull, G., & Sterling, M. (2003). Dizziness and unsteadiness following whiplash injury: Characteristic features and relationship with cervical joint position error. *Journal of Rehabilitation Medicine*, *35*(1), 36–43. https://doi.org/10.1080/16501970306109. PMID: 12610847.

Vald, N. D. (2025). *Vald performance*. Retrieved 26 January from https://valdperformance.com/sports

Van Hoof, W. A., Volkaerts, K. A., O'Sullivan, K. B., Verschueren, S. A., Dankaerts, W. A., & Dankaerts, W. (2015). Low back pain in cycling: Does it matter how you sit? *Journal of Science and Cycling*, *4*(2), 1–2. https://doi.org/10.1136/bjsports-2014-093494.134

Vatovec, R., & Voglar, M. (2024). Changes of trunk muscle stiffness in individuals with low back pain: A systematic review with meta-analysis. *BMC Musculoskeletal Disorders*, *25*(1), 155. https://doi.org/10.1186/s12891-024-07241-3

Weakley, J., Black, G., McLaren, S., Scantlebury, S., Suchomel, T. J., McMahon, E., Watts, D., & Read, D. B. (2024). Testing and profiling athletes: Recommendations for test selection, implementation, and maximizing information. *Strength & Conditioning Journal*, *46*(2), 159–179. https://doi.org/10.1519/SSC.0000000000000784

Wickwire, P. J., Leach, M., Ryder, J., Ploutz-Snyder, R., & Ploutz-Snyder, L. (2011, July 6). Reliability of upright and supine power measurements using an inertial load cycle ergometer (NASA Technical Report No. 20110008129). Paper presented at the National Strength and Conditioning Association Annual Conference, Las Vegas, NV. https://ntrs.nasa.gov/citations/20110008129