

Principal Component Analysis (PCA) Detects a Bilateral First Principal Component (PC1) Score Shift Not Systematically Captured by Conventional Metrics: A Longitudinal Single-Rider Case Study (2014–2025)

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1 Introduction

In practice, power balance (PB)—the ratio of left-to-total power output—is the most commonly used bilateral scalar for assessing pedaling asymmetry (ANT+ Alliance, 2013). PB reflects scalar force magnitude rather than the force-profile shape that characterizes each leg's coordination pattern; asymmetry indices may therefore vary substantially depending on the measurement and analysis approach (Murray et al., 2024). Most commercially available power meters report only power output, and even devices capable of measuring crank forces typically export only scalar summaries per revolution. The Pioneer Pedaling Monitor and

its Shimano-branded equivalent instead record tangential and normal crank forces at 12 discrete crank-angle positions per revolution, enabling force-profile shape analysis that is not available from conventional power meters. A principal component analysis (PCA) framework applied to slope values of these pedal force vector components was evaluated previously in a multi-rider study (Fukuda & Kitawaki, 2026). PC1 was interpreted as reflecting coordinated force production between the pushing and pulling phases, representing a coordination pattern characteristic of each leg's technique and independent of power output magnitude. The present study extends this framework to



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independent bilateral projection using a single-rider longitudinal dataset (2014–2025) to examine whether PCA-derived left–right asymmetry detects patterns that remain undetected by conventional scalar indicators.

2 Material and Methods

A single trained male competitive cyclist (age 41–52 years) was monitored across nine Tour de Okinawa (Gran Fondo 140 km) race events during a 12-year observation period (2014–2025). Data was collected using bilateral crank-arm power meters of the same form factor (Pioneer Pedaling Monitor, 6 events; Shimano equivalent [Ultegra and Dura-Ace], 3 events); the crank length was unchanged throughout. After quality filtering (communication-error and outlier exclusion), 1,327 training activities were included in the analysis. PCA eigenvectors derived from a multi-rider model (Fukuda et al., 2026) were used to project the left and right legs independently, yielding PC1 scores for each leg. Bilateral asymmetry was defined as $\Delta PC1 = PC1_Left - PC1_Right$ (positive values indicate a higher left-leg PC1 score). PB was used as the conventional scalar reference metric.

3 Results and Discussion

PB showed year-to-year variability without a systematic directional trend (range: -1.4% to $+2.3\%$; $L\% - 50$), which may limit its usefulness for longitudinal technique monitoring. In contrast, PC1_Left showed a substantial shift while PC1_Right showed no systematic directional trend (range: -1.44 to $+0.03$; Table 1). Consequently, $\Delta PC1$ increased from 0.12 in 2014 to a peak of 2.06 in 2023 (Figure 1). This divergence was not reflected in PB and suggests greater sensitivity of PCA-derived indices for longitudinal monitoring. Race-day PC1 scores (Figure 1A) equaled or exceeded the training distribution median in eight of nine observed years, broadly consistent with enhanced coordination during peak race preparation. PC1_Left increased during the earlier period (2014–2019), preceding the two major injury events (right shin laceration requiring surgery, February 2020; crash with right clavicle fracture and pneumothorax, June 2023); the rider additionally reported several minor crashes over the period, all on the right side. PC1_Right showed no notable recovery following these events, consistent with the rider's report of persistent limited right-side function. Both legs received equivalent training throughout. Training-period $\Delta PC1$ showed a strong rank correlation with race-day $\Delta PC1$ (Spearman $\rho = 0.88$, $n = 9$ race years).

Table 1. Race-day PC1 scores, bilateral asymmetry index ($\Delta PC1 = PC1_Left - PC1_Right$), and power balance deviation ($PB = L\% - 50$) across nine race events.

Year	PC1_L	PC1_R	$\Delta PC1$	PB (%)
2014	-0.23	-0.35	0.12	+1.33
2015	-1.14	-1.44	0.30	+1.79
2016	-0.84	-1.22	0.39	-0.52
2017	+0.45	-0.11	0.56	+1.34
2018	-0.46	-1.28	0.82	+1.58
2019	+0.51	-0.40	0.91	-1.37
2022	+1.56	-0.28	1.84	-0.11
2023	+1.86	-0.20	2.06	+1.68
2025	+1.30	+0.03	1.27	+2.26

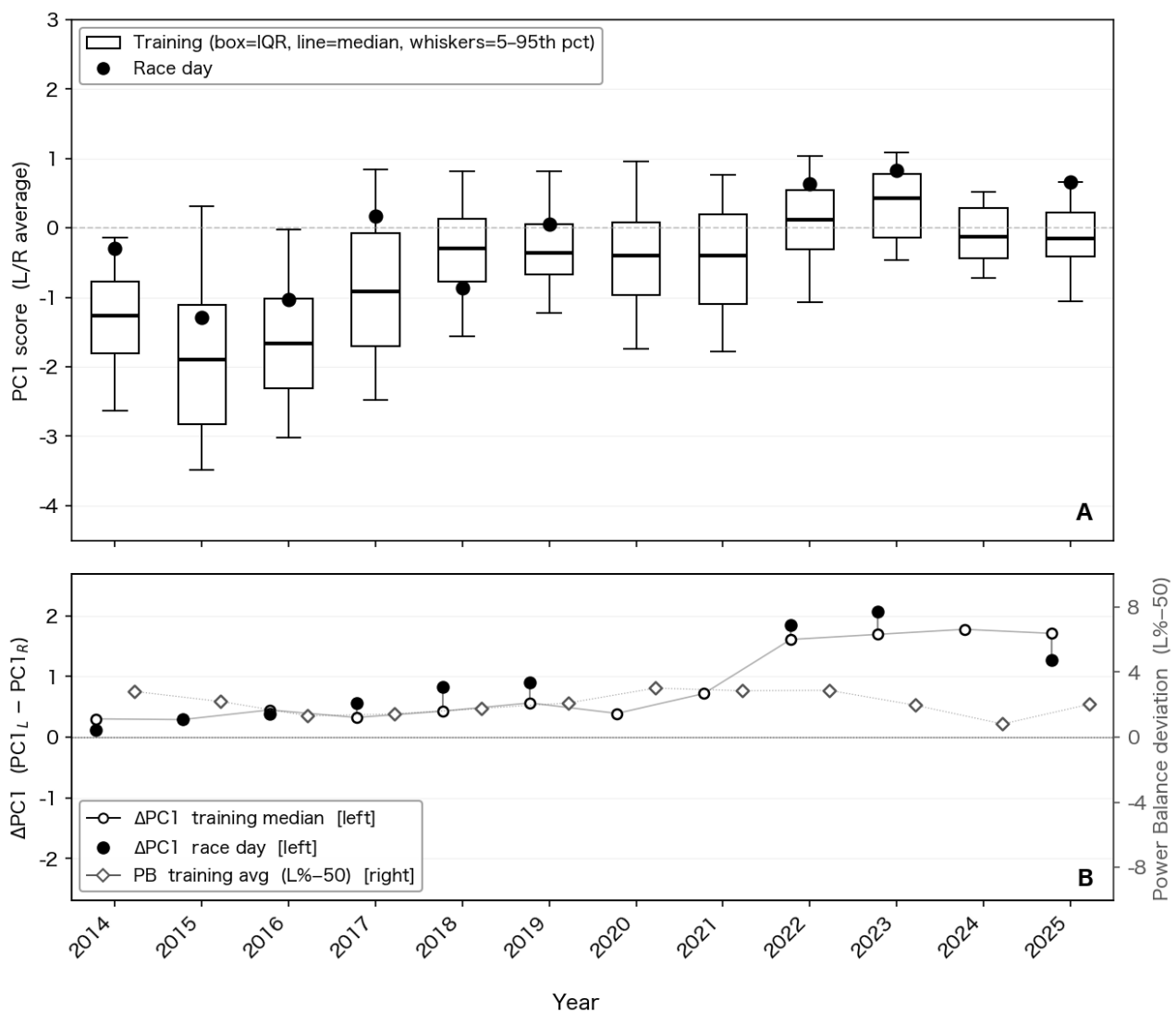


Figure 1. PC1 score trends and bilateral asymmetry index (2014–2025). (A) Annual PC1 score distributions (left/right average; 1,327 quality-filtered training activities). Boxes show IQR; whiskers indicate the 5th–95th percentile; filled circles indicate race-day values. (B) Dumbbell plot: the left group (circles, left axis) represents the Δ PC1 training median (open) connected to race day (filled); the right group (diamonds, right axis, gray) represents power balance deviation (L% – 50) as the annual training average. Short Δ PC1 dumbbell segments indicate consistency between training and race-day contexts. Injuries: right shin laceration (February 2020); crash with right clavicle fracture and pneumothorax (June 2023).

4 Practical Applications

Cyclists equipped with force-sensing power meters (Pioneer Pedaling Monitor or the Shimano equivalent) can apply this PCA framework to monitor bilateral crank-force coordination independently for each leg. Unlike conventional power balance, PCA-derived Δ PC1 reflects force-profile shape and may reveal asymmetric technique changes or injury-related compensatory patterns that remain undetected by scalar power metrics. Coaches and sports scientists may therefore

use longitudinal Δ PC1 trends to complement power-based monitoring when evaluating technique interventions or rehabilitation progress.

5 Conclusions

Δ PC1 (= PC1_{Left} – PC1_{Right}) captured a bilateral asymmetry pattern—characterized by increasing left-leg PC1 values with no systematic directional trend in right-leg PC1—that was not reflected in power balance throughout the observation period. Because both legs received equivalent training, this

pattern is consistent with the rider's self-report that the left leg improved with ordinary training while the right leg was held back by repeated right-side injuries, although these interpretations remain speculative and qualitative. These findings provide proof of concept and warrant replication in larger independent cohorts.

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