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Conference Abstract

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Principal Component Analysis of Pedal Force Vectors Reveals Individual Pedaling Strategies in the Component Scores

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cycling; pedaling force vector; principal component analysis; pedaling strategy; pedaling technique

1 Introduction

In outdoor cycling, workload continuously fluctuates because of variations in road gradient, cruising speed, wind conditions, and group dynamics. Cyclists adapt their pedaling motion in response to these variations. In this study, pedaling strategy is defined as an individual-specific, workload-dependent modulation of force application throughout the crank cycle.

Previous studies have shown that pedaling technique varies according to rider characteristics and that workload influences pedaling mechanics (García-López et al., 2016; Kautz et al., 1991). However, most prior research has focused on absolute force magnitude or peak timing under controlled laboratory conditions. These approaches do not directly quantify how force application changes in response to workload fluctuations in real riding environments.

In our previous work (Fukuda et al., 2026, in press), we demonstrated that instantaneous pedal force at each crank angle exhibits a linear relationship with effective driving force. By expressing this workload dependence as the slope of the tangential and radial force components at each crank angle and applying principal component analysis (PCA), we showed that pedaling characteristics can be reduced to a small number of principal component (PC) scores.

The slope represents the sensitivity of angle-specific force generation to workload changes.

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We hypothesize that this workload sensitivity reflects intrinsic coordination patterns and therefore captures pedaling strategy more directly than absolute force values. The purpose of the present study is to extend this method and clarify the biomechanical meaning of four principal components derived from slope-based PCA of pedal force vectors measured during outdoor cycling.

2 Material and Methods

2.1 Participants

Ninety-one cyclists registered with SHIMANO CONNECT Lab participated in this study. All participants provided comprehensive informed consent. The study was approved by the ethics review board.

2.2 Data Processing

Outdoor ride data were analyzed under natural, unrestricted riding conditions. Target segments were extracted from field data in which workload varied naturally because of environmental and riding factors such as terrain and speed fluctuations. Workload was defined as effective driving force calculated from measured power output and cadence.

For each participant and each crank angle (12 equally spaced angle bins per revolution), linear regression was performed between instantaneous pedal force and workload. The slope of this regression represents the workload sensitivity of force generation at that specific crank angle. Figure 1 illustrates an example of the regression slope calculation.

Both tangential and radial components of the pedal force vector were analyzed. Because each revolution was divided into 12 angular bins, 12 slope values were obtained for the tangential component and 12 for the radial component (24 variables per participant in total). These slope values were mean-centered before analysis. PCA was then conducted, and component retention was determined using the Kaiser criterion (eigenvalue > 1) together with scree plot inspection.

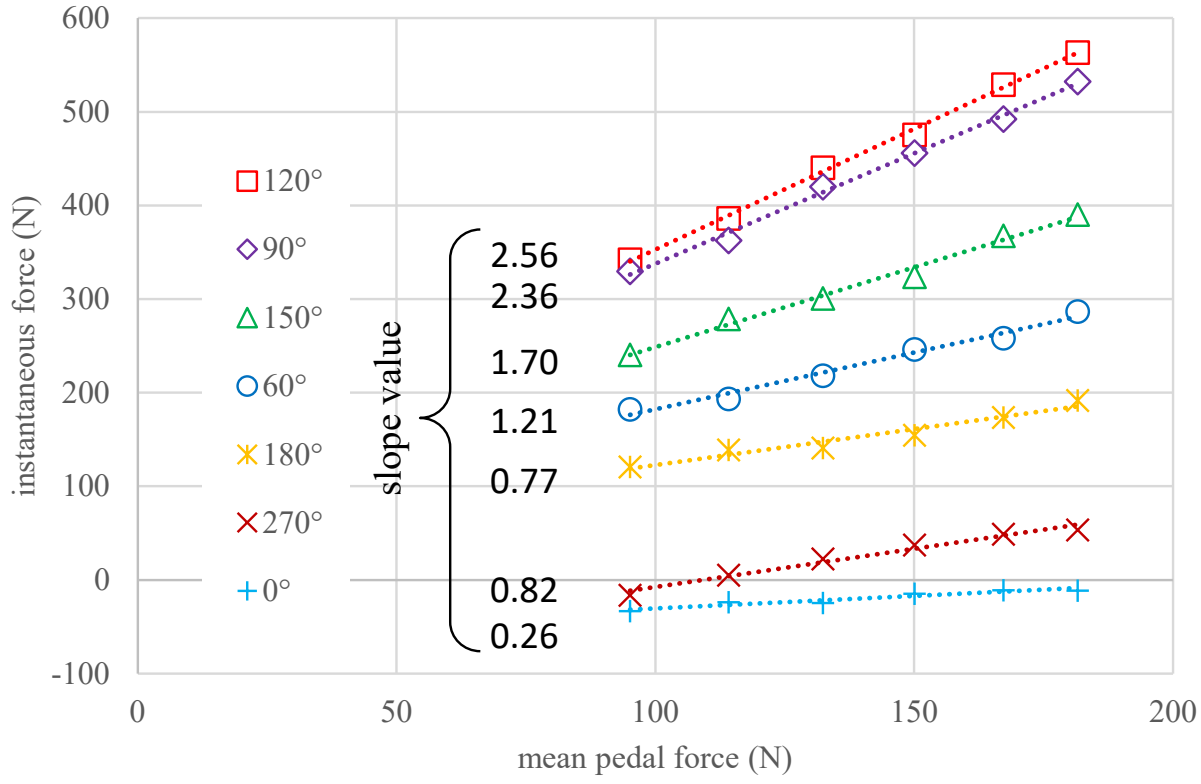


Figure 1. Slope calculation method: Linear approximation against load increase (not all angles).

3 Results and Discussion

3.1 Principal Component Structure

Four principal components were retained. The eigenvalues of PC1 to PC4 were sufficiently large, as shown in Table 1, and the cumulative contribution ratio reached 83.4%. The scree plot showed a clear inflection after PC4, supporting the retention of four components. These results indicate that workload-dependent pedal force characteristics can be effectively summarized using four components. Figure 2 shows the waveforms of these principal components.

Table 1. Characteristics of PC scores.

	Eigen Value	Cumulative Contribution Rate (%)
PC1	3.965	41.2
PC2	2.247	64.6
PC3	1.224	773.
PC4	0.584	83.4

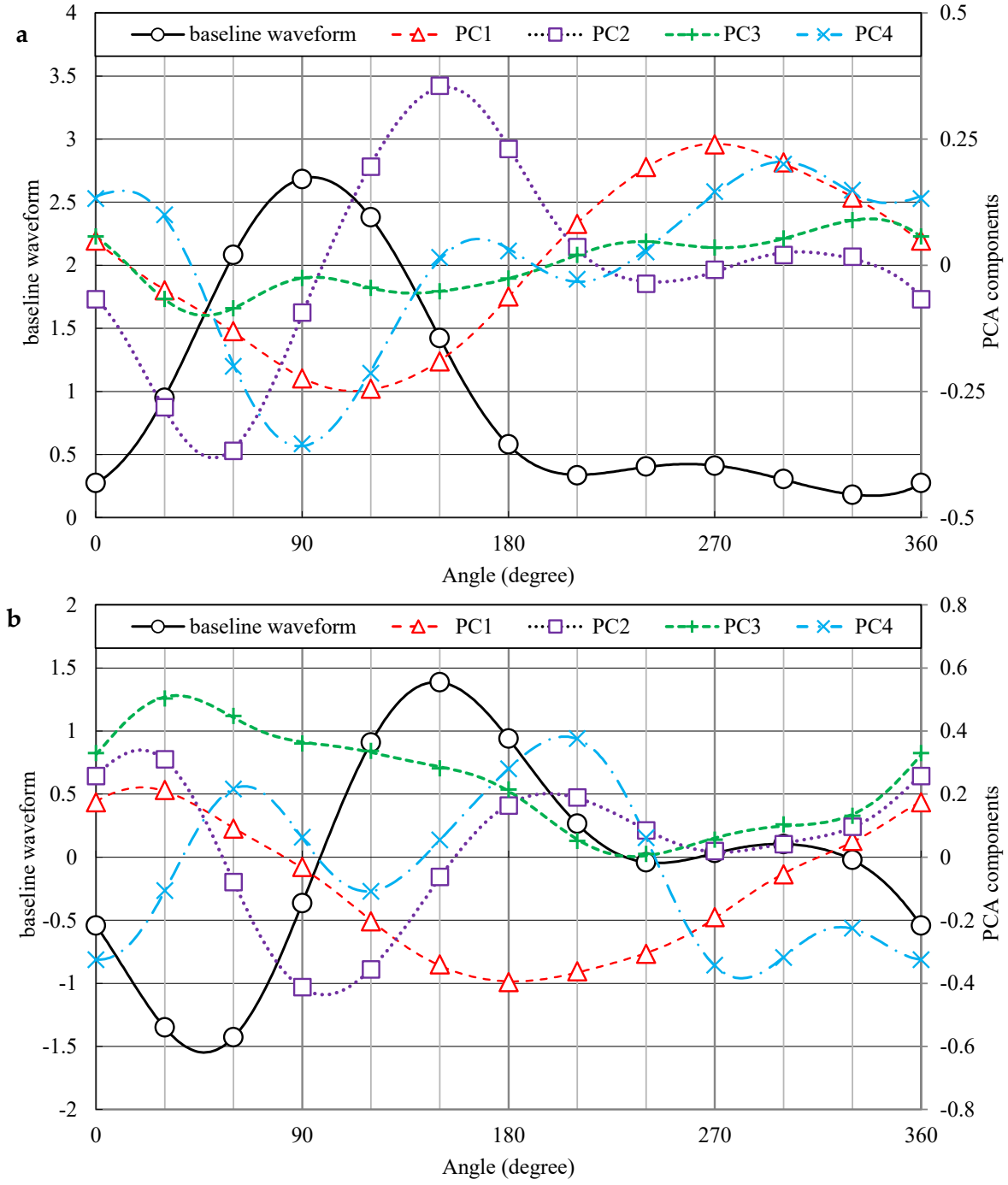


Figure 2. Waveforms of principal components. (a) PC waveform in the tangential direction. (b) PC waveform in the radial direction.

3.2 Biomechanical Interpretation of Principal Components

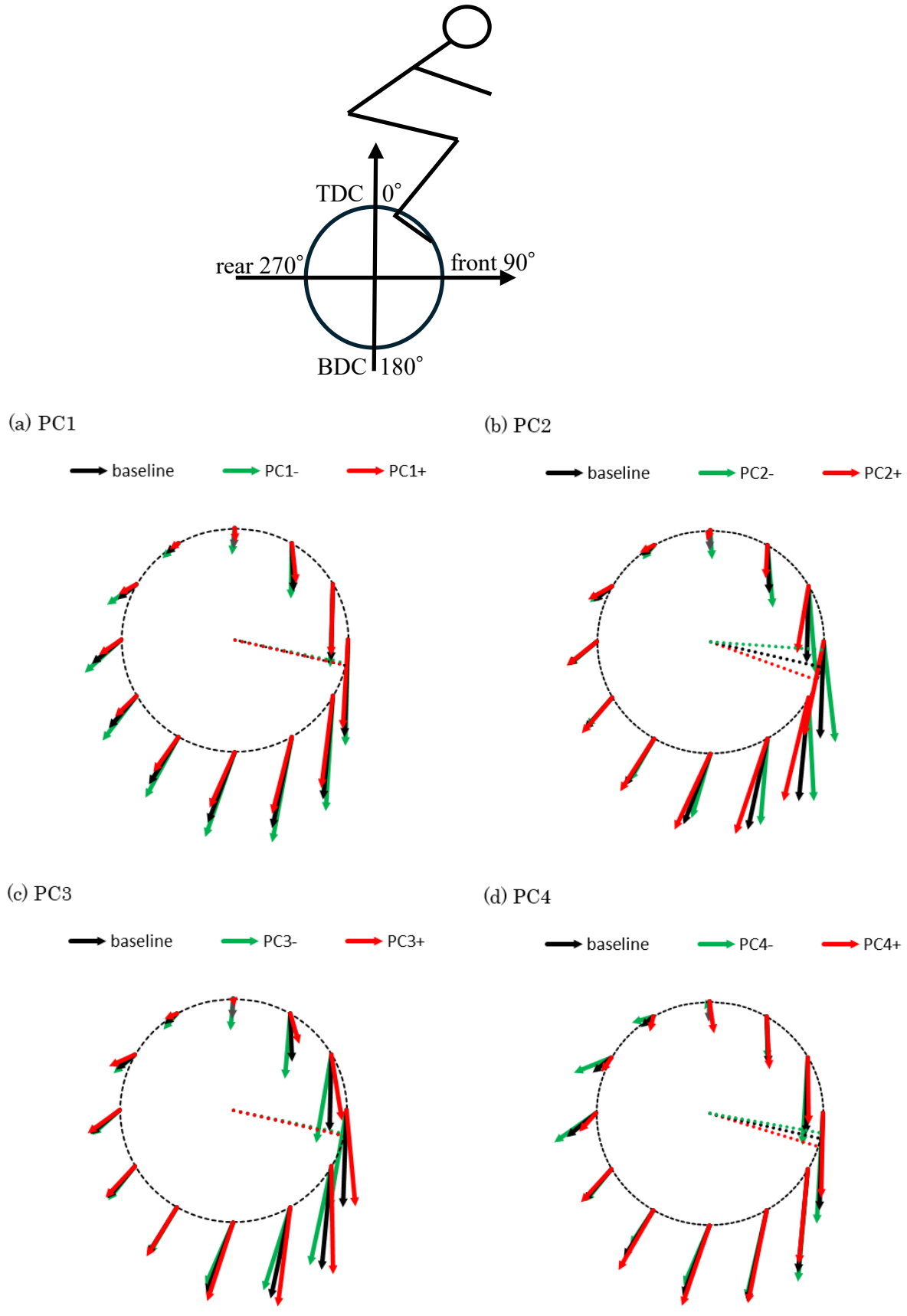


Figure 3. Changes in pedal force vector due to differences in PC1 to PC4

To interpret each principal component, reconstructed pedal force vectors were visualized by varying individual PC scores while holding the remaining components constant (Figure 3). Dashed lines in the inner circles indicate the crank angles corresponding to the estimated peak pedal force. An increase in PC1 was associated with greater upward lifting force during the upstroke phase without requiring a substantial increase in downstroke force, reflecting coordinated force production between the pushing and pulling phases. In contrast, an increase in PC2 shifted the downstroke force direction rearward and delayed the timing of peak tangential force, indicating modulation of both peak timing and force direction. PC3 primarily influenced force patterns between top dead center and early downstroke, where higher PC3 values corresponded to slightly more anteriorly directed force application during initial crank engagement. PC4 represented modulation of the duration of force application; higher PC4 scores were associated with continued upward and forward foot motion during the late upstroke phase, resulting in reduced peak downstroke force and suggesting a strategy emphasizing distributed rather than concentrated force production. Collectively, these four components provide interpretable descriptors of individual pedaling strategies in response to workload variation.

4 Conclusions

Workload-dependent, angle-specific changes in pedal force vectors can be quantified as slope values and reduced through principal component analysis into four interpretable components. These components correspond to coordination between the pushing and pulling phases, modulation of peak timing and direction, anterior engagement during early downstroke, and distribution of force over time.

This slope-based framework captures workload sensitivity rather than absolute force magnitude and provides a practical method for evaluating cyclist-specific pedaling strategies directly from outdoor field data.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. García-López, J., Díez-Leal, S., Ogueta-Alday, A., Larrazabal, J., & Rodríguez-Marroyo, J. A. (2016). Differences in pedalling technique between road cyclists of different competitive levels. Journal of Sports Sciences, 34(17), 1619–1626. https://doi.org/10.1080/02640414.2015.1127987
2. Kautz, S. A., Feltner, M. E., Coyle, E. F., & Baylor, A. M. (1991). The pedaling technique of elite endurance cyclists: Changes with increasing workload at constant cadence. International Journal of Sport Biomechanics, 7(1), 29–53. https://doi.org/10.1123/ijsb.7.1.29
3. Fukuda, M., Koyama, R., Inomata, T., & Kitawaki, T. (2026). Evaluating pedaling strategy using a PCA-based analysis of crank force vectors collected during outdoor cycling. in press to Acta Bioeng Biomech. https://doi.org/10.37190/abb/220441