BOOST - Biomechanical Optimized Observation in Sport Training

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Contents

1 Abstract

BOOST ("Biomechanical Optimized Observation in Sport Training") is an **innovative project** designed to deliver **actionable insights** for athletes seeking to optimize their cycling performances. By conducting a comparative analysis of bicycle configurations, BOOST evaluates the "before" setup, reflecting the athlete's initial preferences, against the "after" setup, fine-tuned based on **precise biomechanical measurements**. The system integrates **advanced motion capture (MoCap) technology** to quantify key biomechanical parameters, such as leg angles, ankle articulation, and spinal alignment. Simultaneously, athletic performance is systematically tracked across multiple training sessions, with **critical metrics** such as power output, speed, and heart rate analyzed to monitor progress or identify areas for improvement. Through this methodology, BOOST could be seen as a **comprehensive framework** for kinematic and performance analysis. The system empowers athletes and even coaches with **detailed assessments** of movement efficiency and postural dynamics, providing a **new powerful tool** in training optimization and injury prevention strategies.

2 Technologies Used

The recordings were conducted using **OptiTrack cameras**, capable of capturing up to **180 frames per second**. These **high-resolution recordings** provide detailed data for **kinematic analysis**. Each athlete wore a suit equipped with 41 markers, enabling precise tracking of pedal mechanics during the recordings. A collection of detailed metrics such as **speed, power, and heart rate** has been collected during training and laboratory sessions, thanks to the usage of **Technogym Ride bikes**. The bikes also facilitated customized training based on each athlete's **Functional Threshold Power (FTP)**. Heart rate monitoring was enabled through athletes connecting their **Apple Watch** or **Polar H10 heart rate monitor**. The **Polar H10** provides **high-accuracy heart rate data** and seamless integration with the training setup.

3 Structure of the Program

To the volunteers was presented the following program:

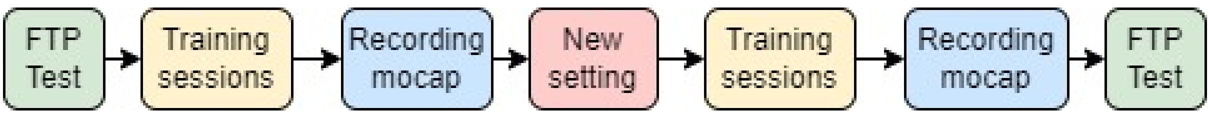


Figure 1: The steps of the program

3.1 FTP Test and Training Program

The initial step in the program required athletes to perform a Functional Threshold Power (FTP) test. This test consisted of cycling at 80% of their maximum effort for 16 minutes, followed by 4 minutes at 100%. The effort enabled the system to calculate each athlete's threshold power. Based on the FTP value, training zones were defined as percentages of this threshold, as illustrated in Figure 2.

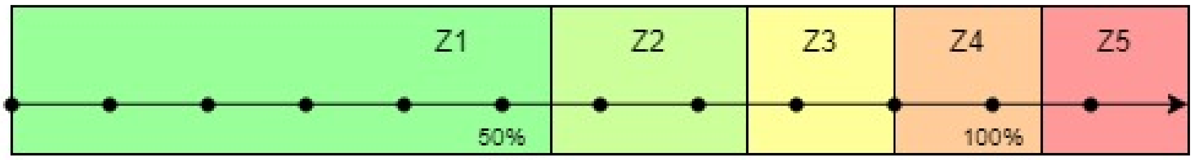


Figure 2: Definition of training zones based on FTP

To enhance vascular capacity and endurance, a standardized training protocol was implemented. Each session lasted 35 minutes and followed the structure shown in Figure 3. The protocol alternated moderate effort levels in Zone 3 with high-intensity intervals in Zone 5. This approach promoted cardiovascular development while minimizing excessive fatigue. Athletes were required to complete this training at least twice a week.

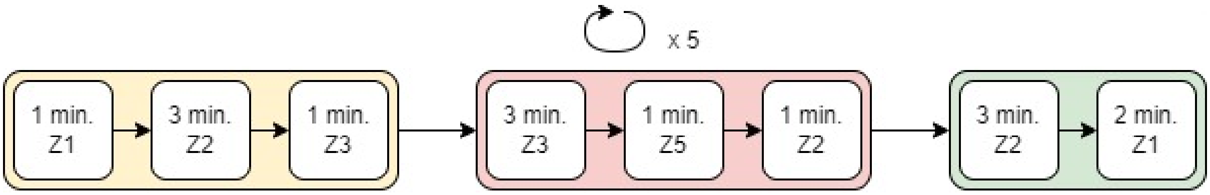


Figure 3: Structure of the proposed workout

3.2 MoCap and Bicycle Settings

In the laboratory, athletes participated in a 5-minute cycling session segmented into distinct effort zones: *2 minutes in Zone 2*, *2 minutes in Zone 3*, and *1 minute in Zone 5*. During the session, a motion capture system equipped with **41 markers** recorded precise data on **leg movements**, **ankle mechanics**, and **spinal posture**. Following this initial recording, the bicycle setup was optimized using **empirical coefficients** derived from the athlete's *inseam* and *torso measurements*.

- **Saddle Height:** Inseam Length $\times$ 0.885
- **Saddle-to-Handlebar Distance:** Torso Length $\times$ 1.11
- **Saddle-to-Handlebar Height Difference:** Inseam Length $\times$ 0.06

These refinements aimed to:

- **Improve mechanical leverage:** Ensuring proper leg extension during pedaling to maximize power output and reduce knee strain.
- **Enhance respiratory efficiency:** Facilitating proper posture to open the diaphragm and support easier breathing during high-intensity efforts.
- **Increase comfort and stability:** Minimizing muscular tension and reducing the risk of fatigue or overuse injuries during prolonged sessions.

This structured approach ensured that each adjustment contributed to **maximizing performance** while minimizing physical strain.

4 Analysis of Data

The analysis focuses on **kinematic and performance data**, comparing the "before" and "after" bicycle settings. Each phase targets specific biomechanical aspects, highlighting changes in joint angles and postural stability.

4.1 Kinematic Analysis

The kinematic analysis assesses three key areas: **spine**, **knees**, and **ankles**. Data is derived from motion capture (MoCap) recordings processed at 30 FPS, focusing on joint angle variations and oscillatory behavior.

4.1.1 Spine

Spinal analysis provides three primary metrics:

- **Back-to-Ground Angle:** Calculated as the inclination of the hip-to-chest axis relative to the ground plane, evaluating upper body alignment (Figure 4d).
- **Stomach Angle:** Defined by the segments hip-to-abdomen and abdomen-to-chest; a higher value approaching 180° indicates improved posture with reduced diaphragm compression(Figure 4e).
- **Lower Back Oscillations:** Midpoint oscillations between hip and chest points capturing spinal dynamic stability during pedaling (Figure 4f).

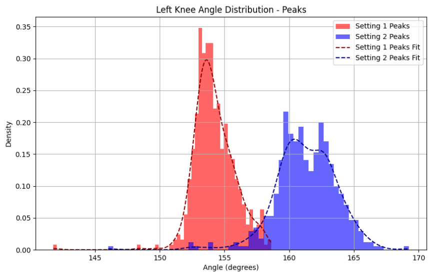
Deviations in the hip-to-chest axis are quantified across training zones. Global metrics include mean oscillation, standard deviation, and average deviations to the left and right. Zone-specific metrics compare oscillations between Zones 2, 3, and 5.

4.1.2 Knees

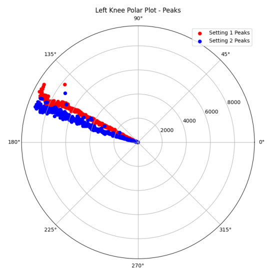
Knee angles are evaluated computing joint angles based on marker positions. The analysis extracts key metrics such as the **mean angle, angular range, and angular velocity** (mean and standard deviation). Trends are visualized using polar plots (Figure 4b) and histograms (Figure 4a), highlighting angular variability over time and their distribution. A detailed analysis of a single cycle (e.g., the 75th cycle) is shown in Figure 4c.

4.1.3 Ankles

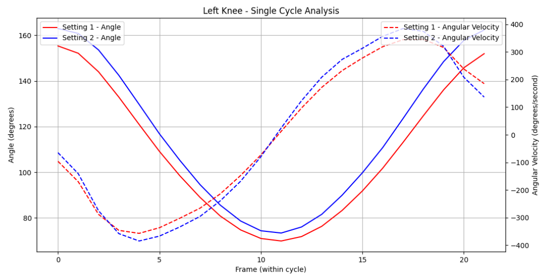
Ankle analysis mirrors the approach for knees, focusing on angles defined by the **shin**, **foot**, and **toe** points of the skeleton rig. Metrics include also in this case **mean angle, cycle amplitude, and cadence**. A single pedaling cycle is analyzed for angular progression and velocity to capture dynamic behavior. The graphs illustrating these analyses are analogous to those shown in Figure 4a, 4b and 4c for the knee.



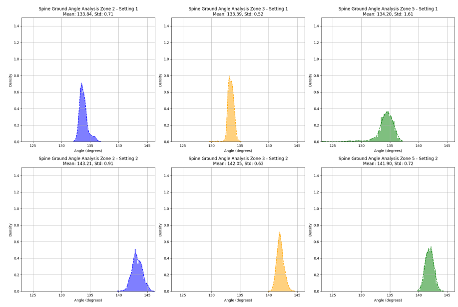
(a) Histograms KDE plots of peaks



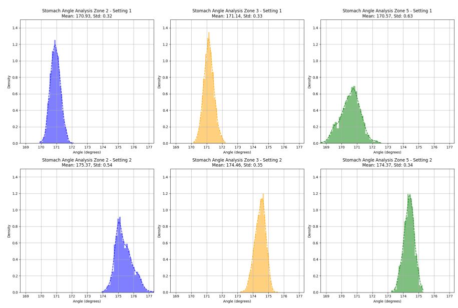
(b) Polar plots shows in a different way the trend of the angles



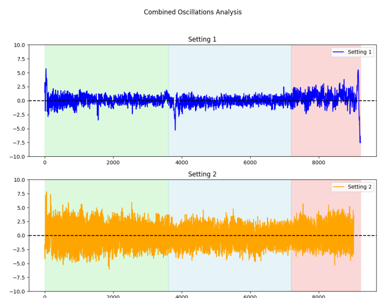
(c) 75th cycle of the knee



(d) Back-to-ground angle analysis



(e) Stomach angle variation



(f) Tail oscillations during cycling

Figure 4: Left knee and spine analysis of an athlete

4.2 Performance Analysis

Performance metrics track **historical trends** in speed, power output, heart rate, and VO2. Metrics are calculated using data processing pipelines that standardize and clean raw data:

- Raw CSV files are loaded, with missing or erroneous values interpolated for continuity.
- Data is grouped into training phases: warm-up, training, and cool-down, based on predefined intervals.
- Maximum and average values for speed, power output, heart rate, and VO2 are computed for each session.

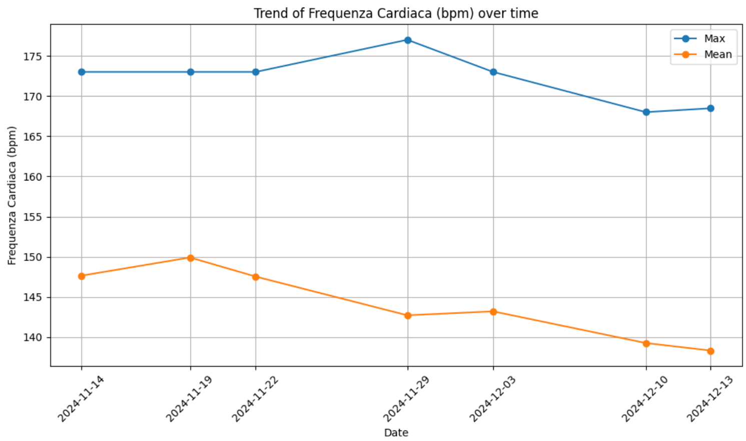
Expected improvements include: **an increase in maximum speed and power output**, reflecting an enhanced performance capacity; **a decrease in average heart rate**, indicating improved cardiovascular efficiency; and **better oxygen utilization (VO2)**, showing an aerobic improvements. To visualize these trends, line graphs are generated, plotting parameters across multiple sessions to identify progress patterns or regressions (Figure 5a).

4.2.1 Single Session Analysis

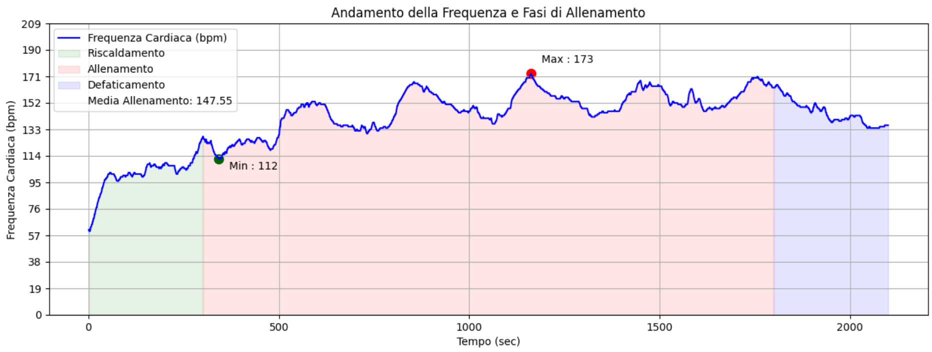
For individual sessions, the analysis examines temporal trends in speed, power output, and heart rate. The workflow includes:

- Segmenting sessions into **phases**: warm-up, training, and cool-down, based on time intervals or physiological markers.
- Plotting parameters against time to observe intra-session dynamics.
- Highlighting training zones on graphs to correlate metrics with specific intensity levels.

The analysis processes session-specific metrics by grouping data within phases and generating descriptive statistics like shown in Figure 5b for the heart-beat.



(a) Heartbeat trend across multiple training sessions.



(b) Heartbeat analysis of a single training session.

Figure 5: Graphs illustrating trends in heartbeat metrics during training sessions.

5 Identified Challenges and Future Developments

5.1 Identified Challenges

Dependency on Volunteers: The participation and consistency of volunteers are critical for data collection. Limited availability can compromise the quality and quantity of the collected information.

Static Definition of FTP: Establishing the Functional Threshold Power (FTP) at the beginning of the program and keeping it unchanged may limit the effectiveness of the training sessions. Regular updates to the FTP, such as weekly adjustments, could accelerate performance improvements, as suggested by scientific literature.

Uniform Bicycle Settings Across Genders: Adopting identical settings for men and women might not account for biomechanical differences between sexes, potentially affecting comfort and training effectiveness.

5.2 Proposals for Future Developments

Collaboration with Biomechanics Experts: Including domain experts could enhance kinematic analysis, enabling deeper assessments, such as:

- Monitoring knee oscillations relative to the axis, identifying inward or outward movements.
- Analyzing shoulder alignment to evaluate weight distribution and postural balance.
- Studying the entire leg lever system instead of focusing solely on joint angles.

Integrated Analysis of Movement and Power Output: Directly linking kinematic data with power output could provide precise insights for correcting inefficiencies and optimizing pedaling technique.

Evaluation of Force Balance Between Limbs: Examining the distribution of force between the left and right legs could highlight asymmetries, guiding targeted corrective interventions.

Monitoring of Lactic Acid Levels: Integrating performance analysis with lactic acid measurements during exercise would offer a more comprehensive understanding of physiological responses to training. This approach could help optimize workloads and prevent muscle fatigue.