AI-Based Kinematic Analysis for Track Athletes

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Outline

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- Prior Works
- Proposed Methodologies
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  - Feature Extraction
  - Posture Classification
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Motivation

- Running involves a complex composition of body segments in motion.
- Crucial for athletes seeking
  - Peak performance
  - Injury prevention
- Traditionally, professional runners relied on customized expensive lab equipment
  - Unnatural/uncomfortable marker-based system
  - Restricting real-world movements
- **Computer vision and video analysis can transform the landscape**
  - **Non-intrusive and transparent**
  - **Accurate kinematic analysis**

Postural Analysis

- Importance
  - Identify and quantify athlete's strengths, weaknesses and progress
  - Improve runner's techniques and postures
  - Minimize the risk of injury
  - Train with a higher precision and confidence

- Our Goal
  - Building a Digital Kinematic Database (runners' recordings for training AI-based models)
  - Automating Pose Detection and Posture Classification
  - Informative Visualization and Expert Validation

Four Phases (Postures) of Running

1. **Toe-Off:** The last frame before the runner's support-leg foot loses contact with the ground

2. **MVP:** Maximal height of vertical projection position where the center of mass (CoM) reaches its highest point on y-axis

1- Toe-Off

2- Maximal Vertical Projection (MVP)

Four Phases (Postures) of Running (Cont.)

3. **Touch-Down:** The first frame where the swing-leg foot strikes the ground

4. **Full-Support:** The frame where the foot is directly under the pelvis – the toe of the foot should be plumb vertical to the pelvis

3- Touch-Down 4- Full-Support

Prior Works

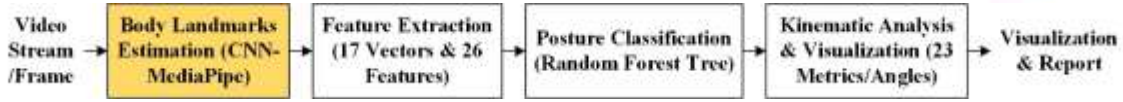
Reference	Key Methodology	Main Application
[10] T. Caporaso, et al.	Wearable IMU system	Analyze race-walking performance, provide real-time feedback
[11] M. Gholami, et al.	Single accelerometer + deep learning	Assess runner kinematics, predict joint angles
[12] K. Takeichi, et al.	Mobile app with pose estimation	Analyze running form, improve running, prevent injuries
[13] J. Wang, et al.	Mobile AI coach with deep HPE	Analyze athletic movements, provide personalized training
[14] A. Dobre, et al.	Video analysis	Detect and address running flaws
[6] D. Pfaff, et al.	ALTIS kinogram (5-frame analysis)	Track sprint mechanics progress, identify areas for improvement

Proposed Methodology

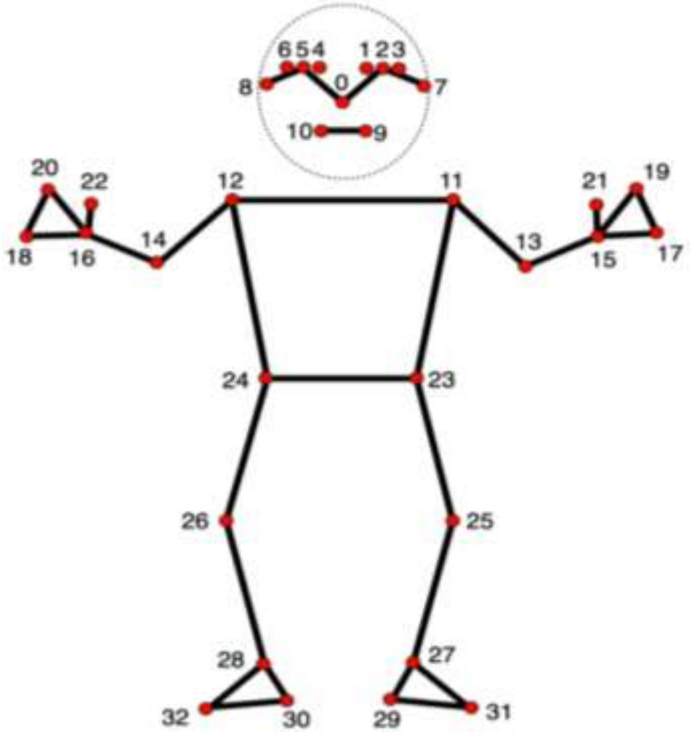
- 30+ Frame per Second
- Multiple Cameras Optional

Video Stream /Frame → Body Landmarks Estimation (CNN-MediaPipe) → Feature Extraction (17 Vectors & 26 Features) → Posture Classification (Random Forest Tree) → Kinematic Analysis & Visualization (23 Metrics/Angles) → Visualization & Report

Body Landmarks Estimation



➢ We have employed the **Mediapipe**'s general pose model to identify the approximate locations of 33 body landmarks.

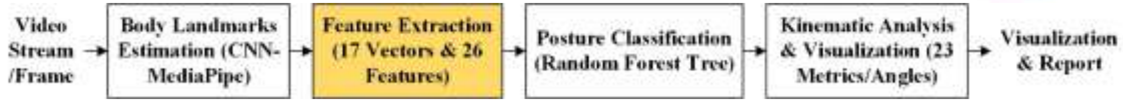


➢ Customizations for running application

- Accurate 3D coordinates (adding depth information)
- Tracking the relevant landmarks effectively
- Dealing with incompleteness and inaccuracies
- Extract useful feature for ML-based models

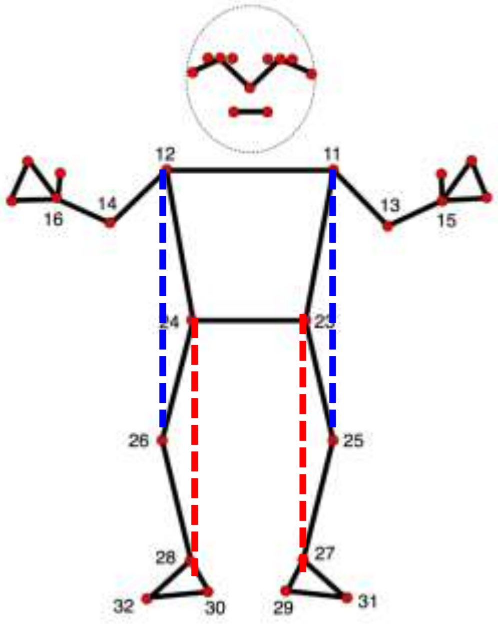
https:/developers.google.com/mediapipe/solutions/vision

Feature Extraction

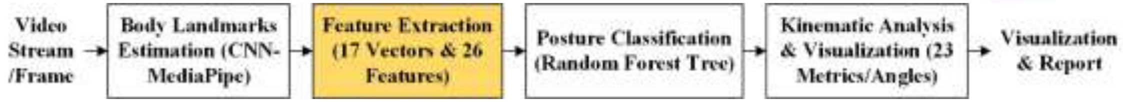


- For accurate kinematic analysis, we extract features relevant to running four phases (postures).
- We chose **16 specific landmarks**, including toes, heels, shoulders, hips, knees, ankles, elbows, and wrists.
- Utilizing these specific landmarks, we construct **17 vectors**

Vector Name	(Start Point, End Point)	
	Left	Right
Foot Line	(31, 29)	(32, 30)
Shin Line	(27, 25)	(28, 26)
Thigh Line	(25, 23)	(26, 24)
Upper Limb Line	(11, 13)	(12, 14)
Forearm Line	(13, 15)	(14, 16)
Wrist-Hip Line	(13, 23)	(16, 24)
Shoulder - Knee Line	(11, 25)	(12, 26)
Hip - Ankle Line	(23, 27)	(24, 26)
Knee Line	(26, 25)	



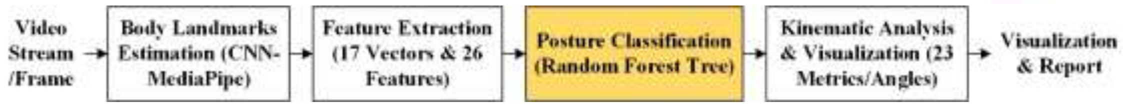
Feature Extraction (Cont.)



- Using 17 vectors constructed, we extract **26 features** that include angles and distances for classification step.

ID	Feature	ID	Feature	ID	Feature
1	Angle Left Foot with x-axis	10	Angle Left Elbow Joint	19	Distance Left Shoulder and Knee
2	Angle Right Foot with x-axis	11	Angle Right Elbow Joint	20	Distance Right Shoulder and Knee
3	Angle Left Knee with x-axis	12	Angle Left Arm with x-axis	21	Angle Left Shoulder and Knee with x-axis
4	Angle Right Knee with x-axis	13	Angle Right Arm with x-axis	22	Angle Right Shoulder and Knee with x-axis
5	Angle Left Thigh with x-axis	14	Angle Left Flexion Joint	23	Distance Left Hip and Ankle
6	Angle Right Thigh with x-axis	15	Angle Right Flexion Joint	24	Distance Right Hip and Ankle
7	Angle Between two Thighs	16	Distance Between two Knees	25	Angle Left Hip and Ankle with x-axis
8	Angle Left Shin with x-axis	17	Distance Left Wrist and Hip	26	Angle Right Hip and Ankle with x-axis
9	Angle Right Shin with x-axis	18	Distance Right Wrist and Hip		

Posture Classification – Challenges



➢ Variability

- Runners exhibit a wide range of variability even for the same posture/activity.
- Factors like body structure, lighting and camera angle further complicate classification.

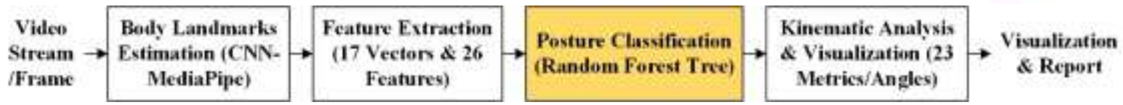
➢ Inaccuracies

- Landmarks detected by MediaPipe can be inaccurate (i.e. noisy data as input for classifier).

➢ Realtime Processing

- Some users may prefer real-time analysis to provide immediate feedback. This puts constraints on the computational efficiency of the algorithm.

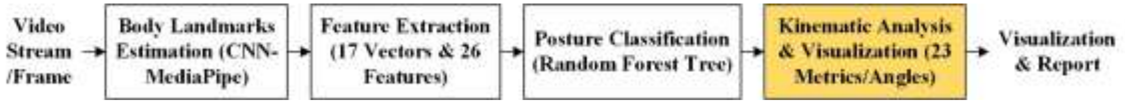
Posture Classification – Method



- **Random Forest:** A machine learning method that combines the strengths of decision trees.
  - Builds multiple decision trees, each using a random subset of the data and random features for splitting decisions.

- Random Forest classifier is known for
  - High accuracy
  - Robustness
  - Flexibility
  - Low sensitivity to noise and outliers

Kinematic Analysis & Visualization – Goals



➢ Posture Improvement

- Identify gait/postural problems such as arched back, leaning head

➢ Personalized and Improved Mechanics

- For each runner, monitor progress in improving the running mechanics

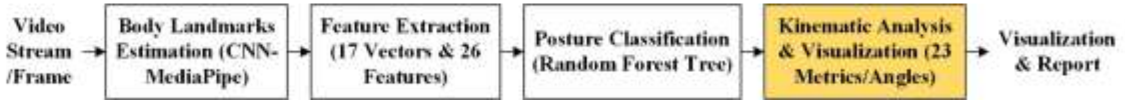
➢ Injury Prevention

- Identify asymmetry or weakness that could lead to injuries

➢ Corrective Training

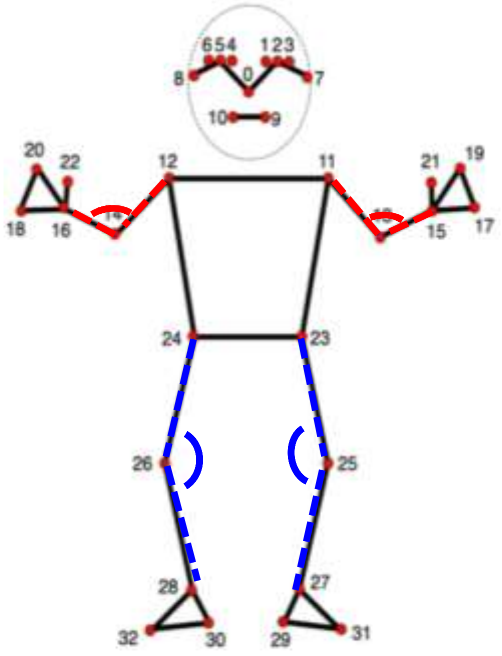
- Design exercises to address tight hip flexors on one side

Kinematic Analysis & Visualization – Analysis



- Comprehensive kinematic analysis is done to determine the key metrics and visualize the results for each posture.

Posture	Empirical Metrics (Expert Selected)	Kinematic Metrics (System Analysis)	Landmarks Involved	
			Left	Right
Toe-Off	1. Stance-leg foot perpendicular to the ground. 2. Incomplete extension at knee joint. 3. 90-degree angle between thighs. 4. Swing-leg toe vertical to swing-leg knee. 5. Rear arm open and front arm close. 6. 90-degree flexion of foot. 7. Forearms perpendicular to each other. 8. Front-leg shin parallel to rear-leg thigh.	1. Foot angle with ground. 2. Knee joint angles. 3. The angle between thighs. 4. Angle of (knee, toe) line with x-axis. 5. Elbow joints angles. 6. The angle of line connects toe, heel, and ankle. 7. Angle of forearm with x-axis. 8. Angle of shins and thighs with x-axis.	1. 31,32 2. 23, 25, 27 3. 23, 25 4. 25, 31 5. 11, 13, 15 6. 31, 29, 27 7. 15, 13 8. 23, 25, 27	1. 29, 30 2. 24, 26, 28 3. 24, 26 4. 26, 32 5. 12, 14, 16 6. 32, 30, 28 7. 14, 16 8. 24, 26, 28
MVP	1. 90-degree angle between thighs. 2. Front-leg knee joint angle more than 110-degree. 3. Dorsiflexion of front leg foot. 4. Neutral head carriage. 5. The head and hip should be straight.	1. Angle between thighs. 2. Knee joint angles. 3. The angle of line connects toe, heel and ankle. 4. Angle of (ears, nose) line with x-axis. 5. Angle (Mid-ears, Mid-hip) line with the x-axis.	1. 23, 25 2. 23, 25, 27 3. 31, 29, 27 4. 7, 0 5. 7, 23	1. 24, 26 2. 24, 26, 28 3. 32, 30, 28 4. 8, 0 5. 8, 24
Touch-Down	1. Knees should be together. 2. Front-leg shin should be perpendicular to the ground. 3. Swing-leg foot should be under gluteals. 4. Dorsiflexion of front-leg foot. 5. Hands parallel to each other. 6. Wrist should be after hip.	**1. Distance of knees from each other.** 2. Angel of shins with ground. **3. Distance of heel from middle of hip.** 4. Angle of line connects toe, heel, and ankle. 5. Elbow joints angle. **6. Distance of wrists from middle of hip.**	1. 25 2. 25, 27 3. 23, 27 4. 31, 29, 27 5. 11, 13, 15 6. 23, 15	1. 26 2. 26, 28 3. 24, 28 4. 32, 30, 28 5. 12, 14, 16 6. 24, 16
Full-Support	1. Dorsiflexion of front leg foot. 2. Swing-leg foot should be under gluteals. 3. Swing-leg thigh approximately 45-degree. 4. Stance-leg yield from touch down.	1. Angle of line connecting toe, heel, and ankle. **2. Distance of heel from middle of hip.** 3. Thigh angles with x-axis. 4. Knee joint angles.	1. 31, 29, 27 2. 23, 27 3. 23, 25 4. 23, 25, 27	1. 32, 30, 28 2. 24, 28 3. 24, 26 4. 24, 26, 28



Experimental Results – Setup & Data Collection

- **Computational Platform**
  - Laptop with 32GB of RAM, an Intel i9-12900HK CPU, and an NVIDIA GeForce RTX 3050 GPU
  - Customized MediaPipe using Python, and TensorFlow Lite for efficient model execution
  - A smartphone (60 fps) camera

- **Three Subjects**
  - Each runner ran twice (from right to left and vice versa) along a 15-meter straight line.

- **6,300 Images (Frames) Collected**
  - 1,500 manually annotated (i.e. ground truth) for classifier training

Experimental Results – Features Extraction Accuracy

- Two experienced coaches graded (scale 1 through 4) the results of analysis for landmarks and features
  1. **The location** of the landmark (16 locations)
  2. **The position** of the related line on the affected body part related to each posture (23 lines)
  3. **The angle/distance** of the connected landmarks (19 angles / 4 distances)

- Average Accuracies

Postures	Location (%)	Lines (%)	Angles (%)
Toe-Off	89.0	89.1	88.1
MVP	95.0	90.2	92.9
Touch-Down	88.7	90.4	95.1
Full-Support	89.8	92.5	91.8
Overall Average	**90.6**	**90.6**	**92.0**

Experimental Results – Classification Performance

- We employed a Random Forest classifier with these parameters
  - The maximum number of trees in the forest = 100
  - Gini index (impurity metrics; probability/entropy-driven branching & split)
  - Maximum depth of trees: SQRT (number of features)
  - 5-fold cross-validation approach for reporting, splitting the data into 80% for training and 20% for testing.

- Average performance (**4 posture classes**) and comparison

Classifier	Accuracy (%)	Mean Error (%)	F1 Score (%)
Random Forest Tree	**89.0**	**0.33**	**91.0**
SVM Polynomial	72.0	0.98	71.0
Gradient Boosted Tree	74.0	0.96	73.0

Experimental Results – Possible Improvement (Toe-Off)

- Front knee joint angle (**106** deg) should be closer to 90 deg
- Rear knee extension (**170** deg) closer to full 180 deg
- Dorsiflexion angle of front foot/ankle (**118**) closer to 90 deg

Features	Value [Left Leg, Right Leg]
Foot Ground Angle	[76.61, 53.2]
Knee Joint Angle	[**170.65**, **106.95**]
Between Thigh Angle	[78]
Knee Toe Angle	[97.04, 108.69]
Elbow Joint Angle	[35.18, 128.92]
Flexion Foot Angle	[126.59, **118.8**]
Forearm X Axis Angle	[105.34, 96.24]
Shin X Axis Angle	[119.64, 105.39]
Thigh X Axis Angle	[39.74, 109.39]

Experimental Results – Possible Improvement (MVP)

- Torso is not fully upright (**99** deg - leaning forward); should be closer to 90 deg
- Front shin is not perpendicular to ground (**75** deg)
- Head carriage (**14.7** deg) can be closer to neutral

Features	Value [Left Leg, Right Leg]
Knee Joint Angle	[142.25, 136.83]
Between Thigh Angle	[70]
Flexion Foot Angle	[106.71, **74.96**]
Ear-Nose X Axis Angle	[**14.7**]
Ear Hip X Axis Angle	[**98.83**]

Experimental Results – Possible Improvement (Touch-Down)

- Swing of recovery (rear) leg too high, resulting in insufficient hip flexion
  - Distance between knees (**0.16 m**) should be minimal
  - Early plantar flexion (**86.49** deg) of front foot upon touch down

Features	Value [Left Leg, Right Leg]
Elbow Joint Angle	[140.39, 139.36]
Flexion Foot Angle	[70.1, **86.49**]
Shin X Axis Angle	[122.36, 88.53]
Distance Knees	[**0.16 m**]
Distance Heel Hip	[0.46 m, 0.83 m]
Distance Wrist Hip	[0.23 m, 0.2 m]

Experimental Results – Possible Improvement (Full Support)

- Most metrics are within acceptable range
- Distance of recovery heel-to-hip (**0.32 m**) can be minimized further

Features	Value [Left Leg, Right Leg]
Knee Joint Angle	[50.37, 158.08]
Flexion Foot Angle	[70.22, 83.81]
Thigh X Axis Angle	[83.61, 76.24]
Distance Heel Hip	[**0.32 m**, 0.85 m]

Experimental Results – Left-Right vs. Right-Left Strides

1. Toe-Off

Angle Between Thighs
(77 vs 69)

2. MVP

Rear Knee Extension Angle
(142 vs 152)

3. Touch-Down

Touchdown Shin Angle
(88 vs 90)

4. Full-Support

Conclusions & Future Work

- The proposed AI- and video-based methodology empowers both coaches and athletes by providing:
  - An automated and comprehensive kinematic analysis during in-field training
  - Informative feedback and visualization
  - A personalized and data-driven analysis to achieve peak performance

- We have shown the feasibility and validated the effectiveness of the kinematic analysis platform for track & field.

- Our future work includes real-time feedback and personalized AI-based coaching

Thanks for Your Attention!

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