# Measurement Methods for Single-Leg Balance Test

## Overview

This document outlines the recommended approach for measuring stability and balance in a computer vision application designed to assess youth athletes (ages 5-13) performing a single-leg balance test.

**Test Protocol:**

- User stands tall on one leg
- Arms extended horizontally in T-position (shoulder height)
- Elevated foot held at approximately 90° knee flexion
- Failure conditions: elevated foot taps the ground, OR arms drop significantly from horizontal

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## Recommended Approach: Euclidean Distance in Cartesian Space

For this specific balance test, tracking **Euclidean displacement of key landmarks in Cartesian (image/world) space** is the optimal method.

### Why This Works

The single-leg balance test is fundamentally about **spatial stability**, not pose similarity. We need to measure:

1. How much the person sways (center of mass proxy displacement)
2. Whether the elevated foot crosses a height threshold (failure detection)
3. Maintenance of the 90° knee angle (form quality)
4. Arm deviation from horizontal T-position (upper body control and compensation indicator)

Euclidean distance in Cartesian space directly answers these questions by measuring actual physical displacement of body points.

### Key Landmarks to Track (MediaPipe)

| Landmark | Index | Purpose |
|---|---|---|
| Left Hip | 23 | CoM proxy (sway measurement) |
| Right Hip | 24 | CoM proxy (sway measurement) |

| Landmark | Index | Purpose |
|---|---|---|
| Left Ankle | 27 | Foot position / failure detection |
| Right Ankle | 28 | Foot position / failure detection |
| Left Knee | 25 | Angle maintenance check |
| Right Knee | 26 | Angle maintenance check |
| Left Shoulder | 11 | Torso height normalization, arm baseline |
| Right Shoulder | 12 | Torso height normalization, arm baseline |
| Left Wrist | 15 | Arm deviation tracking |
| Right Wrist | 16 | Arm deviation tracking |

### Implementation Approach

**Hip Sway Calculation:** Calculate the Euclidean displacement of the hip midpoint from its baseline position captured at test start. Track both X (lateral) and Y (vertical) displacement, computing the resultant vector magnitude.

**Failure Detection:** Monitor the elevated ankle's Y-coordinate relative to the standing ankle. In MediaPipe, Y increases downward, so failure occurs when the elevated ankle Y approaches or exceeds the standing ankle Y minus a small threshold.

**Knee Angle Calculation:** Compute the angle at the knee joint using vectors from knee-to-hip and knee-to-ankle. The dot product formula yields the angle in radians, converted to degrees for interpretability. Target is approximately 90° flexion.

**Arm Deviation Calculation:** For the T-position, measure how far each wrist drops below its corresponding shoulder height. The ideal T-position has wrists at shoulder level (zero deviation). Key measurements include:

- **Total Arm Deviation:** Sum of left and right wrist drop from shoulder height
- **Arm Asymmetry:** Difference between left and right wrist drop (indicates lateral instability)
- **Individual Arm Drop:** Per-side deviation for detailed analysis

Arm deviation serves dual purposes: (1) as a form quality metric, and (2) as a compensation indicator—excessive arm movement often signals the body recruiting upper-body strategies to maintain balance.

### Normalization Strategy

Since test subjects range from ages 5-13 with significant size variance, normalize all distance measurements by **torso height** (vertical distance from shoulder midpoint to hip midpoint).

Express sway, arm deviation, and other displacement metrics as a percentage of torso height. This aligns with the Percentage of Correct Keypoints (PCK) methodology, where thresholds are defined relative to body size.

For arm deviation specifically, normalization ensures that a 5cm wrist drop means different things for a small 5-year-old versus a larger 13-year-old.

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## Why T-Position for Arms?

The T-position (arms extended horizontally at shoulder height) offers several advantages over hands-on-hips for youth balance assessment:

### Biomechanical Benefits

| Factor | T-Position | Hands on Hips |
|---|---|---|
| Moment of inertia | Higher (more baseline stability) | Lower |
| Compensation visibility | High—deviations obvious | Not visible |
| Baseline definition | Clear horizontal reference | N/A |
| Asymmetry detection | Easy to spot lateral imbalance | Not possible |

### Arms as a Balance Indicator

With arms extended horizontally, they function like a tightrope walker's balance pole:

- **Any tilt is immediately apparent** in the video feed
- **Arm drop indicates compensation attempt**—the body recruiting upper-body strategy
- **Asymmetric arm position reveals lateral instability**—one side working harder
- **Deviation from horizontal is easy to quantify** against the shoulder baseline

### Research Support

Studies show that arm contribution to balance increases significantly when task difficulty increases. For youth populations specifically:

- Children and adolescents show greater performance differences between free and restricted arm movement during high-difficulty balance tasks compared to adults
- The effect of arm restriction is more pronounced in youth (ages 10-14) than young adults
- Arm movement serves as a compensatory mechanism that is especially important for individuals with still-developing postural control systems

This makes arm tracking particularly valuable for the 5-13 age group, where the postural control system is not yet fully mature.

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## Alternative Methods: Trade-offs and Limitations

### Euclidean Distance in Joint Space

**Description:** Measures the straight-line distance between two joint angle configurations (e.g., comparing knee angle, hip angle, etc. as a vector).

**Trade-offs:**

| Pros | Cons |
|---|---|
| Compact representation of whole-body pose | Proximal vs. distal joint weighting problem |
| Good for pose matching/classification | Same angular change = different physical displacement |
| Computationally simple | Doesn't capture actual spatial movement |

**Limitations for Balance Test:**

- A 5° wobble at the hip creates much larger body displacement than a 5° wobble at the ankle, but joint-space Euclidean distance treats them equally
- Fails to directly measure what we care about: physical stability
- Poor correlation with actual balance performance
- Cannot directly detect foot-ground contact (failure condition)

**When to Use Instead:** Pose classification tasks, comparing static poses, gesture recognition.

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**DISP (Displacement-based) Distance**

**Description:** Measures the actual spatial displacement of points on the body model as configuration changes. Accounts for kinematic chain effects.

**Trade-offs:**

| Pros | Cons |
| --- | --- |
| More physically meaningful than joint-space Euclidean | Requires full kinematic model with segment lengths |
| Captures end-effector displacement accurately | Computationally more expensive |
| Better for comparing movement quality | Overkill for simple stability measurement |
| Accounts for body proportions | Adds complexity without proportional benefit for this use case |

**Limitations for Balance Test:**

- Designed for comparing two different poses/movements, not tracking deviation from a baseline position
- Requires accurate segment length measurements (challenging with 2D pose estimation)
- Added complexity doesn't improve failure detection or sway measurement
- Better suited for skill comparison (e.g., "how similar is this throw to a reference throw?")

**When to Use Instead:** Movement quality assessment, skill transfer analysis, comparing technique across athletes.

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**Object Keypoint Similarity (OKS)**

**Description:** Calculates similarity score between predicted and ground truth keypoints, accounting for scale and visibility. Used in COCO pose estimation benchmarks.

**Trade-offs:**

| Pros | Cons |
|---|---|
| Scale-invariant | Designed for pose estimation accuracy, not movement analysis |
| Handles keypoint visibility | Requires ground truth pose for comparison |
| Industry standard for model evaluation | Not designed for temporal stability measurement |

**Limitations for Balance Test:**

- Intended for evaluating pose estimation model accuracy, not measuring human performance
- Requires a "ground truth" pose to compare against
- Single-frame metric; doesn't capture temporal stability
- Visibility weighting not relevant for balance assessment

**When to Use Instead:** Evaluating pose estimation model performance, benchmarking against datasets.

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### Center of Pressure (CoP) Analysis

**Description:** Gold standard in balance research. Measures the point of application of ground reaction force using force plates.

**Trade-offs:**

| Pros | Cons |
|---|---|
| Gold standard for balance assessment | Requires force plate hardware |
| Direct measurement of balance control | Not possible with camera-only setup |
| Clinically validated metrics | Expensive equipment |

**Limitations for Balance Test:**

- Cannot be measured with computer vision alone
- Requires specialized hardware not available in target deployment environment
- Not feasible for a mobile/accessible youth assessment tool

**When to Use Instead:** Clinical gait labs, research studies with proper equipment, validation of CV-based methods.

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#### Center of Mass (CoM) Estimation

**Description:** Estimate whole-body center of mass position using segment mass distributions and landmark positions.

**Trade-offs:**

| Pros | Cons |
|---|---|
| More biomechanically accurate than single-point tracking | Requires segment mass percentages (age/sex dependent) |
| Better proxy for true balance state | Added complexity and potential error sources |
| Research-validated approach | 2D CoM estimation has inherent limitations |

**Limitations for Balance Test:**

- Segment mass distributions vary significantly in growing children
- Standard adult segment parameters don't apply to youth population
- Hip midpoint serves as reasonable CoM proxy for upright stance
- Marginal accuracy improvement doesn't justify added complexity for MVP

**When to Use Instead:** Research applications, adult populations with known anthropometrics, when higher precision is required.

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### Method Comparison Summary

| Method | Spatial Accuracy | Complexity | Hardware Needs | Youth Suitability | Balance Test Fit |
|---|---|---|---|---|---|
| **Cartesian Euclidean (Recommended)** | High | Low | Camera only | Excellent | ★★★★★ |
| Joint-Space Euclidean | Low | Low | Camera only | Good | ★★☆☆☆ |

| Method | Spatial Accuracy | Complexity | Hardware Needs | Youth Suitability | Balance Test Fit |
| --- | --- | --- | --- | --- | --- |
| DISP Distance | High | Medium | Camera only | Moderate | ★★★☆☆ |
| OKS | N/A | Low | Camera only | Good | ★☆☆☆☆ |
| Center of Pressure | Highest | High | Force plate | Poor (equipment) | ★☆☆☆☆ |
| CoM Estimation | High | Medium | Camera only | Moderate | ★★★☆☆ |

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## Recommended Scoring Framework

Based on the Cartesian Euclidean approach:

### Primary Metrics

1. **Pass/Fail:** Did the elevated foot touch the ground, or did arms drop excessively?
2. **Hold Duration:** Time maintained before failure (or total test duration)
3. **Sway Score:** Average normalized hip displacement from baseline (lower = better)
4. **Knee Form Score:** Consistency of knee angle maintenance around 90°
5. **Arm Deviation Score:** Average normalized wrist drop from shoulder height (lower = better)
6. **Arm Asymmetry:** Difference in left vs. right arm deviation (lower = more balanced)

### Scoring Tiers (Example)

| Tier | Criteria |
| --- | --- |
| Excellent | No failure, sway < 3% torso height, knee angle within ±10°, arm deviation < 5% torso height |
| Good | No failure, sway < 5% torso height, knee angle within ±15°, arm deviation < 8% torso height |
| Developing | No failure, sway < 8% torso height, knee angle within ±20°, arm deviation < 12% torso height |
| Needs Work | Failure before time limit, or metrics outside "Developing" range |

**Interpreting Arm Metrics**

Arm deviation provides insight beyond simple form compliance:

| Pattern | Interpretation |
| --- | --- |
| Low arm deviation + Low hip sway | Strong balance control, minimal compensation needed |
| High arm deviation + Low hip sway | Using arm strategy effectively to maintain stability |
| Low arm deviation + High hip sway | Poor balance control, not utilizing available compensation |
| High arm deviation + High hip sway | Struggling to maintain balance despite compensation attempts |
| High arm asymmetry | Lateral instability; one side consistently working harder |

Research indicates that arm movement restriction affects children and adolescents more than adults during difficult balance tasks, making arm tracking particularly relevant for the 5-13 age group.

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