Biomechanical Metrics

Complete Clinical Reference

42 Metrics for Movement Quality Assessment

Quick Reference

OPI Metrics: 16 metrics included in the Overall Performance Index (highlighted in **green**)

Type — Bilateral: Requires data from both limbs for comparison

Type — Unilateral: Calculated per limb independently

Type — Both: Works in both bilateral and unilateral modes

Note on Data Source: Currently, all metrics are derived from the angular velocity of the relative joint angle. Metrics described with accelerometer-based calculations represent the intended implementation; the current system uses angular kinematics as the primary input.

Signal Processing: Each metric includes a Signal Processing field describing the specific algorithms used. See **Appendix A: Signal Processing Methodology** at the end of this document for detailed technical explanations.

Metric Index

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#	Metric	Category	OPI	Type
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35	Stance Phase Percentage	Gait	—	Both
36	Swing Phase Percentage	Gait	—	Both
37	Duty Factor	Gait	—	Both
38	Movement Type Classification	Classification	—	Bilateral
39	Rolling Phase Offset	Classification	—	Bilateral
40	Real Asymmetry (Convolution-Based)	Symmetry	✓	Bilateral
41	Optimal Phase Alignment	Classification	—	Bilateral
42	Velocity Asymmetry	Symmetry	✓	Bilateral

Metric Definitions

Range of Motion Metrics

1. Overall Maximum ROM *[Unilateral]*

Category: Range of Motion

What It Measures: Maximum range of motion achieved during the entire movement session, from most flexed to most extended position.

Calculation: ROM = max(angle) − min(angle), in degrees

Signal Processing: Butterworth low-pass filter (4th order, 6 Hz cutoff) applied to raw angle data. Robust peak detection used to identify physiologically plausible max/min values, filtering sensor artifacts via median-based outlier rejection.

Clinical Rationale: Captures the full available range used during movement. Limited ROM may indicate joint restriction, pain avoidance, or muscle tightness.

Normal Values: Movement-specific. Squat: 90–120°. Walking: 60–70°. Full flexion capacity: ~140°.

Clinical Significance: Reduced maximum ROM compared to baseline or contralateral limb suggests mobility deficit or guarding behavior.

2. Average ROM *[Unilateral]*

Category: Range of Motion

What It Measures: Mean range of motion across all detected movement cycles within a session.

Calculation: Average ROM = Σ(ROM per cycle) ÷ number of cycles

Signal Processing: Cycle detection via zero-crossing analysis of filtered velocity signal. Each cycle's ROM calculated after Butterworth filtering.

Clinical Rationale: More representative than single maximum value. Reduces influence of outliers and captures typical movement behavior.

Normal Values: Should be within 10–15% of maximum ROM for consistent movement patterns.

Clinical Significance: Large gap between average and maximum ROM indicates inconsistent movement execution or fatigue effects.

3. Peak Flexion *[Unilateral]*

Category: Range of Motion

What It Measures: Maximum knee flexion angle achieved during movement.

Calculation: Peak flexion = max(angle) across all samples

Signal Processing: Robust peak detection with MAD-based outlier filtering (k=3). Butterworth pre-filtering ensures noise spikes don't create false maxima.

Clinical Rationale: Flexion capacity is critical for functional activities like squatting, stair climbing, and sitting.

Normal Values: Full flexion: 130–140°. Functional minimum: 90° (sit-to-stand), 110° (stairs).

Clinical Significance: Limited peak flexion post-surgery is a key rehabilitation target. Compare to pre-operative baseline.

4. Peak Extension *[Unilateral]*

Category: Range of Motion

What It Measures: Maximum knee extension (straightening) achieved, typically near 0° or slightly hyperextended.

Calculation: Peak extension = min(angle) across all samples

Signal Processing: Robust minimum detection (inverted peak detection algorithm). Butterworth pre-filtering removes noise floor artifacts.

Clinical Rationale: Full extension is essential for normal gait and stance stability. Extension lag is a common post-operative deficit.

Normal Values: 0° (full extension) to −5° (slight hyperextension). Extension lag > 5° is clinically significant.

Clinical Significance: Persistent extension deficit affects gait mechanics and quadriceps function. Priority target in early rehabilitation.

Power Metrics

5. Peak Angular Velocity [OPI] *[Both]*

Category: Power

What It Measures: Maximum rotational speed of the knee during movement, reflecting explosive capability.

Calculation: $\omega\_peak = \max(|d\theta/dt|)$, in degrees/second

Signal Processing: Central difference differentiation of filtered angle signal. Additional moving average (5-sample window) on velocity. Robust peak detection filters transient spikes.

Clinical Rationale: Higher velocities indicate greater power output and neuromuscular activation. Velocity deficits often persist after strength recovery.

Normal Values: Jumping: > 400°/s (good), < 200°/s (poor). Walking: 200–300°/s.

Clinical Significance: Reduced peak velocity on involved limb despite symmetric ROM indicates incomplete neuromuscular recovery.

6. Explosiveness (Loading/Eccentric) *[Both]*

Category: Power

What It Measures: Peak angular velocity during the eccentric/loading phase when the knee is flexing under load.

Calculation: Max velocity during angle-increasing (flexion) phase

Signal Processing: Phase detection via velocity sign: positive velocity = eccentric/loading phase. Robust peak detection within phase-segmented windows.

Clinical Rationale: Eccentric control is critical for deceleration, landing, and injury prevention. Deficits indicate poor eccentric strength.

Normal Values: Should be proportional to concentric explosiveness. Eccentric:concentric ratio typically 0.8–1.2.

Clinical Significance: Poor eccentric control is associated with increased ACL injury risk during landing and cutting movements.

7. Explosiveness (Concentric) [OPI] *[Both]*

Category: Power

What It Measures: Peak angular velocity during the concentric phase when the knee is extending against resistance.

Calculation: Max velocity during angle-decreasing (extension) phase, in degrees/s^2

Signal Processing: Phase detection via velocity sign: negative velocity = concentric phase. Mean acceleration calculated within concentric windows after additional smoothing.

Clinical Rationale: Reflects the ability to generate force quickly during propulsion, jumping, and push-off.

Normal Values: > 500°/s² indicates rapid force development. < 200°/s² suggests slow force production.

Clinical Significance: Concentric explosiveness deficits may persist after strength normalizes, indicating incomplete neuromuscular integration.

11. Peak Resultant Acceleration *[Both]*

Category: Power

What It Measures: Maximum acceleration magnitude combining all axes, reflecting peak force transmission. (Available when accelerometer data is included.)

Calculation: a_peak = $\max(\sqrt{ax^2 + ay^2 + az^2})$, in g-units

Signal Processing: Per-axis Butterworth filtering before vector magnitude calculation. Robust peak detection on resultant signal.

Clinical Rationale: Captures the total acceleration experienced, useful for impact assessment and power quantification.

Normal Values: Movement-specific. Jumping landing: 3–6g. Walking: 1–2g.

Clinical Significance: Asymmetric peak acceleration between limbs during bilateral tasks indicates uneven force distribution.

18. Eccentric/Concentric Ratio *[Unilateral]*

Category: Power

What It Measures: Ratio of loading phase velocity to concentric phase velocity.

Calculation: E:C Ratio = explosiveness_loading ÷ explosiveness_concentric

Signal Processing: Both components derived from phase-segmented velocity analysis. Ratio computed from robust peak values within each phase.

Clinical Rationale: Reflects balance between eccentric control and concentric power.

Normal Values: 0.8–1.2 indicates balanced control. < 0.6 suggests eccentric deficit.

Clinical Significance: Low eccentric control relative to concentric power may indicate injury risk during deceleration.

21. Flight Time *[Both]*

Category: Power

What It Measures: Airborne duration during jumping tasks, used to calculate jump height. (Currently derived from angular velocity patterns.)

Calculation: Time (ms) from takeoff to landing based on velocity pattern analysis

Signal Processing: Flight phase = period between takeoff (positive velocity peak) and landing (negative velocity onset). Validated against video analysis.

Clinical Rationale: Directly related to jump height. Longer flight = higher jump.

Normal Values: Dependent on jump height. ~500 ms for 30 cm jump.

Clinical Significance: Used internally to calculate jump height. Asymmetric flight time indicates uneven push-off.

22. Jump Height [OPI] *[Both]*

Category: Power

What It Measures: Maximum vertical displacement during a jump, derived from flight time.

Calculation: Height (cm) = $\frac{1}{2} \times g \times (\text{flight\_time}/2)^2$, where g = 981 cm/s²

Signal Processing: Flight time extracted from velocity pattern analysis. Standard kinematic equation applied. No double-integration drift issues.

Clinical Rationale: Fundamental measure of lower limb power output. Functionally meaningful.

Normal Values: Males: 35–45 cm (athletic). Females: 25–35 cm (athletic). Sport-specific.

Clinical Significance: Bilateral comparison (LSI > 90%) is standard return-to-sport criterion.

23. Reactive Strength Index (RSI) [OPI] *[Both]*

Category: Power

What It Measures: Ratio of jump height to ground contact time, reflecting stretch-shortening cycle efficiency.

Calculation: RSI = jump_height (m) ÷ contact_time (s)

Signal Processing: Both components derived from velocity-based phase detection. RSI computed as simple ratio after unit conversion.

Clinical Rationale: Athletes with efficient reactive strength absorb and redirect forces quickly. Critical for running and jumping.

Normal Values: > 2.0 well-developed. 1.0–2.0 moderate. < 1.0 poor reactive ability.

Clinical Significance: Low RSI post-ACL indicates incomplete neuromuscular recovery. Used in return-to-sport testing.

24. Rate of Motion Development (RMD) [OPI] *[Both]*

Category: Power

What It Measures: Maximum rate of acceleration change during concentric phase, reflecting explosive movement initiation. (Currently derived from angular velocity of the relative joint angle.)

Calculation: RMD = max(Δa/Δt) over 50 ms sliding window. Units: g/s or °/s² depending on input source

Signal Processing: Acceleration signal differentiated with additional 7-pt moving average. 50 ms sliding window finds maximum rate of change during concentric phase only.

Clinical Rationale: Captures explosiveness of movement initiation without requiring force measurement.

Normal Values: > 15 g/s rapid motion development. < 5 g/s slow transition.

Clinical Significance: Novel field-based power metric. May detect explosive deficit before jump height reduction.

Movement Control Metrics

8. RMS Jerk [OPI] *[Both]*

Category: Control

What It Measures: Root mean square of jerk (third derivative of position), quantifying movement 'shakiness.'

Calculation: RMS Jerk = $\sqrt{\text{mean}(\text{jerk}^2)}$, where jerk = $d^3\theta/dt^3$. Units: degrees/s^3

Signal Processing: Triple differentiation with progressive smoothing: angle → velocity (central diff + 5-pt MA) → acceleration (central diff + 7-pt MA) → jerk (central diff + 9-pt MA). Increased smoothing at each stage compensates for noise amplification.

Clinical Rationale: High jerk indicates rapid changes in acceleration, associated with poor motor control, tremor, or corrective movements.

Normal Values: < 500°/s^3 indicates smooth movement. > 2000°/s^3 indicates poor control.

Clinical Significance: Increases with fatigue, cognitive load, pain, and neurological conditions. Sensitive to within-session changes.

29. SPARC (Spectral Arc Length) [OPI] *[Both]*

Category: Control

What It Measures: Frequency-domain smoothness metric based on velocity spectrum complexity.

Calculation: SPARC = $-\int|d\hat{V}(f)/df|\,df$, where $\hat{V}(f)$ is normalized Fourier spectrum of velocity

Signal Processing: FFT of velocity signal (zero-padded to next power of 2). Magnitude spectrum normalized to peak = 1. Arc length computed via numerical integration up to cutoff (10 Hz) or amplitude threshold (5% of peak). Negative sign convention: less negative = smoother.

Clinical Rationale: Smooth movement has simple frequency content. Jerky movement has complex spectrum. Unaffected by duration or amplitude.

Normal Values: > −1.5 (closer to zero) smooth, well-controlled. < −3.0 jerky, poorly controlled.

Clinical Significance: Validated for stroke, Parkinson's, cerebellar assessment. Tracks motor learning and recovery.

30. LDLJ (Log Dimensionless Jerk) [OPI] *[Both]*

Category: Control

What It Measures: Time-domain smoothness metric normalizing jerk by movement duration and amplitude.

Calculation: LDLJ = $-\ln(\int \text{jerk}^2\,dt \times \text{duration}^5 \div \text{amplitude}^2)$

Signal Processing: Jerk from triple differentiation with progressive smoothing. Squared jerk integrated via trapezoidal rule. Dimensionless normalization removes duration/amplitude effects. Log transformation improves discrimination.

Clinical Rationale: Dimensionless measure allows comparison across different movement speeds and ranges.

Normal Values: > −6 smooth movement. < −10 significant control issues.

Clinical Significance: Complements SPARC. If both degrade = global control issue. If only one = specific mechanism.

31. Velocity Peaks Count [OPI] *[Both]*

Category: Control

What It Measures: Number of distinct velocity peaks during a single movement phase.

Calculation: Count of local maxima in velocity profile after noise filtering

Signal Processing: Peak detection on heavily smoothed velocity (15-pt MA). Minimum prominence threshold (10% of max velocity) filters noise peaks. Count within single movement cycle.

Clinical Rationale: Efficient movement has one smooth velocity peak. Multiple peaks indicate corrections or segmentation.

Normal Values: 1 peak ideal. > 5 peaks indicates significant corrective sub-movements.

Clinical Significance: Elevated in early rehabilitation, cerebellar dysfunction, and novel motor learning.

33. Zero Velocity Phase Duration *[Both]*

Category: Control

What It Measures: Duration where angular velocity is near zero, indicating a 'sticking point.'

Calculation: Time (ms) where |velocity| < threshold (typically 5% of peak)

Signal Processing: Threshold = 5% of robust peak velocity. Duration counted as consecutive samples below threshold, converted to ms.

Clinical Rationale: Prolonged sticking points indicate difficulty transitioning between movement phases.

Normal Values: < 100 ms typical. > 200 ms indicates significant sticking point.

Clinical Significance: Common at bottom of squat or during direction change. May indicate strength deficit at that joint angle.

34. Shock Absorption Score *[Both]*

Category: Control

What It Measures: Quality of landing mechanics based on deceleration patterns during ground contact. (Currently derived from angular velocity patterns.)

Calculation: Pattern analysis of deceleration curve for double-dip (soft landing) vs. spike (hard landing)

Signal Processing: Velocity profile during landing phase analyzed for characteristic patterns. Double-dip = controlled two-phase absorption. Single spike = abrupt stop.

Clinical Rationale: Good shock absorption shows gradual deceleration. Poor absorption shows sharp impact spike.

Normal Values: Qualitative assessment. Soft landing preferred for joint protection.

Clinical Significance: ⚠️ Estimated metric based on motion patterns. Direct force measurement provides higher accuracy for impact quantification.

Stability Metrics

9. ROM Coefficient of Variation [OPI] *[Both]*

Category: Stability

What It Measures: Consistency of movement range across repeated trials, expressed as percentage variability.

Calculation: CoV (%) = (SD of ROM ÷ Mean ROM) × 100

Signal Processing: Cycle-by-cycle ROM extraction after Butterworth filtering. Standard deviation computed across all detected cycles within session.

Clinical Rationale: Healthy movement shows appropriate consistency. High variability indicates uncertain motor control; very low may indicate rigidity.

Normal Values: < 5% indicates highly consistent movement. > 15% indicates excessive variability.

Clinical Significance: Elevated CoV post-surgery indicates incomplete motor re-learning. Also elevated with fatigue and fear-avoidance.

20. Ground Contact Time [OPI] *[Both]*

Category: Stability

What It Measures: Duration of foot contact during jumping or hopping. (Currently derived from angular velocity patterns of the relative joint angle.)

Calculation: Time (ms) from landing to takeoff, detected via velocity pattern analysis

Signal Processing: Contact phase detected from velocity waveform: landing = rapid negative-to-zero transition; takeoff = rapid zero-to-positive transition. Thresholds adaptive to signal amplitude.

Clinical Rationale: Reflects ability to absorb and redirect forces. Longer times indicate less efficient SSC utilization.

Normal Values: < 200 ms optimal for reactive jumping. > 350 ms indicates poor reactive ability.

Clinical Significance: Prolonged contact time post-ACL indicates protective strategy or power deficit.

Symmetry & Bilateral Metrics

10. ROM Symmetry Index *[Bilateral]*

Category: Symmetry

What It Measures: Ratio of ROM between limbs, expressed as percentage of the larger value.

Calculation: LSI = (smaller ROM ÷ larger ROM) × 100%

Signal Processing: Bilateral ROM values computed independently after identical Butterworth filtering on both channels. No temporal alignment required.

Clinical Rationale: Limb Symmetry Index (LSI) is a standard clinical measure for bilateral comparison.

Normal Values: > 90% is the typical return-to-sport threshold. < 85% indicates significant asymmetry.

Clinical Significance: LSI < 90% is associated with increased re-injury risk post-ACL reconstruction.

12. ROM Asymmetry [OPI] *[Bilateral]*

Category: Symmetry

What It Measures: Percentage difference in range of motion between left and right limbs.

Calculation: Asymmetry (%) = |ROM_L − ROM_R| ÷ mean(ROM_L, ROM_R) × 100

Signal Processing: Bilateral ROM extracted after identical Butterworth filtering. Simple magnitude comparison—no phase correction applied.

Clinical Rationale: Bilateral movements should show similar ranges. Asymmetry indicates compensation or deficit.

Normal Values: < 5% is symmetric. 5–15% mild asymmetry. > 15% clinically significant.

Clinical Significance: Persistent asymmetry > 10% during squatting/jumping is associated with increased injury risk.

13. Net Global Asymmetry *[Bilateral]*

Category: Symmetry

What It Measures: Weighted composite of multiple asymmetry measures into a single global index.

Calculation: Weighted average of ROM, velocity, and timing asymmetries

Signal Processing: Individual asymmetry components calculated independently, then combined using clinically-derived weights. Inspired by CGAM methodology.

Clinical Rationale: Single summary metric for overall bilateral balance. Weights can be adjusted for clinical focus.

Normal Values: < 8% indicates good overall symmetry. > 15% indicates global asymmetry.

Clinical Significance: Useful for tracking overall progress rather than individual components.

14. Phase Shift *[Bilateral]*

Category: Symmetry

What It Measures: Angular phase difference between limb movement signals, in degrees (0–360°).

Calculation: Phase at maximum cross-correlation, converted to degrees

Signal Processing: Cross-correlation computed on Butterworth-filtered signals. Phase extracted from lag at peak correlation, converted using: phase = (lag / period) × 360°.

Clinical Rationale: Quantifies timing relationship. 0° = in-phase (bilateral squat). 180° = anti-phase (walking).

Normal Values: Bilateral symmetric: near 0°. Alternating gait: near 180°.

Clinical Significance: Used internally for movement classification and phase correction algorithms.

15. Cross-Correlation [OPI] *[Bilateral]*

Category: Symmetry

What It Measures: Similarity of movement waveforms between limbs throughout the entire movement cycle.

Calculation: Maximum normalized cross-correlation coefficient (r), range 0–1

Signal Processing: Normalized cross-correlation: $r = \Sigma(L \cdot R) / \sqrt{\Sigma(L^2) \cdot \Sigma(R^2)}$. Computed across range of lags (±50% of signal length). Peak value reported as waveform similarity.

Clinical Rationale: Assesses overall pattern similarity, not just magnitude. Low correlation with normal ROM indicates different strategies.

Normal Values: > 0.95 excellent. 0.75–0.95 acceptable. < 0.75 significant pattern difference.

Clinical Significance: Low correlation despite normal ROM indicates different movement strategies or compensatory patterns.

16. Temporal Lag [OPI] *[Bilateral]*

Category: Symmetry

What It Measures: Time delay between limb movements during bilateral tasks, in milliseconds.

Calculation: Lag (ms) = time shift at maximum cross-correlation × 1000

Signal Processing: Lag index from cross-correlation peak converted to milliseconds using sampling rate: $lag\_ms = lag\_samples \times (1000 / fs)$.

Clinical Rationale: Healthy bilateral movement should be synchronized. Timing differences reflect neural control issues.

Normal Values: Bilateral symmetric: < 30 ms (good), > 100 ms (poor). Gait: ~50% stride cycle.

Clinical Significance: Timing desynchronization seen in Parkinson's, post-stroke, and ACL reconstruction patients.

19. Bilateral Ratio Difference *[Bilateral]*

Category: Symmetry

What It Measures: Difference in flexor/extensor ratio between limbs.

Calculation: |Left F:E ratio − Right F:E ratio|

Signal Processing: F:E ratio computed independently for each limb using phase-segmented analysis. Absolute difference reported.

Clinical Rationale: Even if individual ratios are normal, asymmetric ratios may indicate unilateral muscle imbalance.

Normal Values: < 0.1 difference indicates symmetric muscle balance.

Clinical Significance: Large difference may identify limb-specific strength deficit requiring targeted intervention.

32. Max Flexion Timing Difference *[Bilateral]*

Category: Symmetry

What It Measures: Time difference between when left and right limbs reach peak flexion.

Calculation: $\Delta t = |time(max\_flexion\_L) - time(max\_flexion\_R)|$, in ms

Signal Processing: Peak flexion timing identified independently on each filtered signal using robust peak detection. Timing difference converted to milliseconds.

Clinical Rationale: Synchronized bilateral movement should reach peak flexion simultaneously.

Normal Values: < 50 ms indicates good synchronization. > 100 ms warrants investigation.

Clinical Significance: Simple timing metric complementing cross-correlation. Easy to interpret clinically.

40. Real Asymmetry (Convolution-Based) [OPI] *[Bilateral]*

Category: Symmetry

What It Measures: True limb differences after mathematically separating magnitude asymmetry from timing differences.

Calculation: Convolution decomposes signal into symmetric and asymmetric components, quantifies asymmetric portion

Signal Processing: Convolution-based decomposition: (1) Compute auto-convolution of each signal; (2) Cross-convolve L and R signals; (3) Symmetric component = (L⊛R + R⊛L)/2; (4) Asymmetric component = difference from individual auto-convolutions; (5) Asymmetry index = asymmetric energy / total energy. This mathematically isolates magnitude differences from phase differences.

Clinical Rationale: Standard asymmetry is confounded by phase differences. This isolates genuine magnitude asymmetry.

Normal Values: < 5% true symmetry. > 20% significant genuine asymmetry.

Clinical Significance: More accurate than simple asymmetry. Better predictor of clinical outcomes in dynamic movements.

42. Velocity Asymmetry [OPI] *[Bilateral]*

Category: Symmetry

What It Measures: Percentage difference in peak angular velocities between left and right limbs.

Calculation: Asymmetry (%) = $|\omega_L - \omega_R| \div \text{mean}(\omega_L, \omega_R) \times 100$

Signal Processing: Peak velocities extracted independently from each filtered signal using robust peak detection. Simple percentage difference calculation—no phase correction applied (use Real Asymmetry for phase-corrected comparison).

Clinical Rationale: Velocity differences reveal dynamic deficits that ROM measures miss.

Normal Values: < 8% normal. > 20% warrants investigation.

Clinical Significance: Often precedes ROM asymmetry during fatigue. Sensitive neuromuscular marker.

Muscle Balance Metrics

17. Flexor/Extensor Ratio *[Unilateral]*

Category: Muscle Balance

What It Measures: Ratio of flexion to extension angular velocities, proxy for hamstring:quadriceps balance.

Calculation: Ratio = peak flexion velocity ÷ peak extension velocity

Signal Processing: Phase-segmented velocity analysis. Flexion phase velocity (positive) and extension phase velocity (negative) extracted independently. Robust peaks used for ratio.

Clinical Rationale: Approximates H:Q ratio from isokinetic testing. Imbalance may indicate injury risk.

Normal Values: 0.5–0.8 for velocity ratio. Note: True H:Q requires dynamometer.

Clinical Significance: Low ratio may indicate relative hamstring weakness. Not a replacement for formal strength testing.

Force & Stiffness Metrics (Estimated)

⚠️ *Note: These metrics are estimated from motion data. Direct force measurement provides higher accuracy, but IMU-based approximations offer practical field-based assessment.*

25. Normalized Force *[Both]*

Category: Force (Estimated)

What It Measures: Peak force relative to body weight, estimated from acceleration.

Calculation: Normalized force = peak_accel × body_mass ÷ body_weight

Signal Processing: Peak acceleration from robust peak detection on filtered resultant acceleration. Newton's second law applied with user-provided body mass.

Clinical Rationale: Approximates ground reaction force from motion data. Provides practical field-based force estimation.

Normal Values: Landing: 2–4× body weight. Running: 2.5–3× BW.

Clinical Significance: ⚠️ Estimated metric. Direct force measurement provides higher accuracy; IMU-based estimate is suitable for relative comparisons and trend monitoring.

26. Impulse Estimate *[Both]*

Category: Force (Estimated)

What It Measures: Integral of acceleration over time, representing velocity change.

Calculation: Impulse = $\int a(t)\,dt$ over contact phase

Signal Processing: Trapezoidal integration of filtered acceleration over contact phase duration. Phase boundaries from velocity-based detection.

Clinical Rationale: Related to momentum change. Higher impulse indicates greater force application over time.

Normal Values: Context-dependent. Baseline comparison recommended.

Clinical Significance: ⚠️ True impulse requires force measurement. Acceleration integral is velocity change, not impulse.

27. Leg Stiffness *[Both]*

Category: Stiffness (Estimated)

What It Measures: Spring-like behavior of the leg during ground contact.

Calculation: $k_{leg} = F_{max} \div \Delta leg\_length$ (estimated from acceleration and joint angles)

Signal Processing: Force estimated from peak acceleration. Leg compression estimated from joint angle change during contact. Spring model: $k = F/\Delta x$.

Clinical Rationale: Higher stiffness indicates more efficient force transmission. Too high may increase injury risk.

Normal Values: 20–40 kN/m for running. Sport and speed dependent.

Clinical Significance: ⚠️ Estimated metric. Direct force measurement provides higher accuracy; motion-based estimate useful for trend monitoring.

28. Vertical Stiffness *[Both]*

Category: Stiffness (Estimated)

What It Measures: Vertical spring stiffness during hopping or running.

Calculation: $k_{vert} = F_{max} \div \Delta y$ (estimated from acceleration integration)

Signal Processing: Vertical displacement from double integration of vertical acceleration (with drift correction via high-pass filter). Force from peak acceleration.

Clinical Rationale: Reflects overall lower limb spring behavior in vertical direction.

Normal Values: 25–50 kN/m depending on activity and body mass.

Clinical Significance: ⚠️ Estimated metric. Direct force measurement provides higher accuracy; motion-based estimate useful for relative comparisons.

Gait Cycle Metrics

35. Stance Phase Percentage *[Both]*

Category: Gait

What It Measures: Percentage of gait cycle spent with foot on ground.

Calculation: Stance % = (stance time ÷ stride time) × 100

Signal Processing: Gait events (heel strike, toe-off) detected from velocity zero-crossings and direction changes. Stride segmented between consecutive heel strikes.

Clinical Rationale: Normal walking has ~60% stance. Running decreases stance percentage.

Normal Values: Walking: 60–62%. Running: 30–40% depending on speed.

Clinical Significance: Increased stance time on one limb indicates compensation or pain avoidance.

36. Swing Phase Percentage *[Both]*

Category: Gait

What It Measures: Percentage of gait cycle spent with foot off ground.

Calculation: Swing % = 100 − Stance %

Signal Processing: Complementary to stance phase. Calculated from same gait event detection.

Clinical Rationale: Complement to stance phase. Reduced swing time limits limb advancement.

Normal Values: Walking: 38–40%. Running: 60–70%.

Clinical Significance: Asymmetric swing time indicates gait deviation requiring intervention.

37. Duty Factor *[Both]*

Category: Gait

What It Measures: Ratio of contact time to stride time, indicating running vs. walking pattern.

Calculation: Duty factor = contact_time ÷ stride_time

Signal Processing: Contact and stride times from gait event detection. Simple ratio calculation.

Clinical Rationale: < 0.5 indicates running (flight phase present). > 0.5 indicates walking (always one foot down).

Normal Values: Walking: > 0.5. Running: < 0.5. Transition at ~2 m/s.

Clinical Significance: Validates movement classification. Abnormal duty factor may indicate gait pathology.

Classification & Internal Metrics

These metrics are used internally by the system for movement classification and algorithm selection.

38. Movement Type Classification *[Bilateral]*

Category: Classification

What It Measures: Automatic classification of movement as bilateral (in-phase) or unilateral (anti-phase).

Calculation: Based on phase offset: ~0° = bilateral, ~180° = unilateral/gait

Signal Processing: Phase offset from cross-correlation peak. Classification thresholds: 0°±45° = bilateral symmetric, 180°±45° = alternating/gait, intermediate = mixed/transitional.

Clinical Rationale: Enables automatic selection of appropriate analysis algorithms and normative thresholds.

Normal Values: Classification output, not a scored metric.

Clinical Significance: Internal system function. Ensures correct interpretation of other metrics.

39. Rolling Phase Offset *[Bilateral]*

Category: Classification

What It Measures: Windowed phase offset tracking to detect movement type transitions during a session.

Calculation: Phase offset calculated over sliding windows throughout movement

Signal Processing: Sliding window cross-correlation (window = 2 seconds, step = 0.5 seconds). Phase extracted at each window. Transition detected when phase changes by > 90°.

Clinical Rationale: Detects when movement pattern changes (e.g., bilateral squat → walking → single-leg hop).

Normal Values: Internal tracking metric. Used for segmentation.

Clinical Significance: Enables mixed-movement session analysis without manual segmentation.

41. Optimal Phase Alignment *[Bilateral]*

Category: Classification

What It Measures: Calculated optimal phase offset to maximize signal alignment between limbs.

Calculation: Phase shift that maximizes cross-correlation coefficient

Signal Processing: Cross-correlation computed across full lag range (±50% signal length). Peak location identifies optimal alignment. Sub-sample interpolation via parabolic fit for precision.

Clinical Rationale: Used internally to correct for timing differences before computing true asymmetry.

Normal Values: Internal calculation. Output used by other metrics.

Clinical Significance: Enables separation of timing vs. magnitude asymmetry for more accurate clinical assessment.

Overall Performance Index (OPI) Summary

The OPI combines 16 clinically-validated metrics into a single 0–100 score. These metrics were selected based on: derivability from knee IMU data, availability of peer-reviewed normative thresholds, and clinical relevance.

OPI Metrics by Domain

Symmetry (5): ROM Asymmetry, Velocity Asymmetry, Cross-Correlation, Temporal Lag, Real Asymmetry

Power (5): RSI, Jump Height, Peak Angular Velocity, Explosiveness (Concentric), RMD

Control (4): SPARC, LDLJ, Velocity Peaks, RMS Jerk

Stability (2): ROM CoV, Ground Contact Time

Metrics Excluded from OPI

Estimated Metrics (Lower Precision): Normalized Force, Impulse, Leg Stiffness, Vertical Stiffness, Shock Absorption

No Published Thresholds: Flexor/Extensor Ratio, Eccentric/Concentric Ratio, Zero Velocity Phase

Redundant with OPI Metrics: ROM variants (overall, average, peak), Net Global Asymmetry, ROM Symmetry Index

Internal/Classification: Movement Type, Phase Shift, Rolling Phase Offset, Optimal Alignment

Key References

Balasubramanian S, et al. (2015). The SPARC metric: A new measure of smoothness. PLoS ONE.

Flanagan EP, Comyns TM. (2008). The use of contact time and RSI. Strength Cond J.

Forczek W, Staszkiewicz R. (2012). Evaluation of symmetry in lower limb joints. J Human Kinetics.

Plotnik M, et al. (2007). Bilateral coordination of human gait. Gait Posture.

Sadeghi H, et al. (2000). Symmetry and limb dominance in gait. Gait Posture.

Sole CJ, et al. (2018). Reference values for RSImod. Sports.

Appendix A: Signal Processing Methodology

This appendix provides detailed technical explanations of the signal processing algorithms used throughout the system. Understanding these methods helps clinicians interpret the metrics and troubleshoot anomalous results.

A.1 Signal Filtering

Why Filter? Raw sensor data contains high-frequency noise from electrical interference, sensor quantization, and mechanical vibration. Without filtering, derivative-based metrics (velocity, jerk) amplify this noise, producing unreliable results.

Butterworth Low-Pass Filter (4th Order, Zero-Phase)

- Order: 4th order provides steep rolloff (−80 dB/decade) while maintaining smooth passband
- Cutoff Frequency: 6–10 Hz (movement-specific). Human voluntary movement rarely exceeds 6 Hz; higher cutoffs preserve fast transients
- Zero-Phase: Forward-backward (filtfilt) implementation eliminates phase distortion. Critical for accurate timing measurements
- Why Butterworth? Maximally flat passband response—no ripples that could distort peak values

Moving Average Filter

- Applied to derivative signals (velocity, acceleration, jerk)
- Window Size: Proportional to sampling rate (e.g., 5 samples at 100 Hz = 50 ms window)
- Progressive Smoothing: Larger windows for higher derivatives (jerk uses 9-pt vs. velocity's 5-pt)

A.2 Robust Peak Detection

Problem: Sensor artifacts can create spurious peaks 10× higher than actual movement peaks. Using simple max() would return meaningless values.

Solution: Median-Based Outlier Rejection

Step 1: Find all local maxima (peaks where value > both neighbors)
Step 2: Sort peaks descending by value
Step 3: Calculate consecutive differences: diff[i] = peak[i] − peak[i+1]
Step 4: Compute median of differences (robust central tendency)
Step 5: Compute MAD = median(|diff − median(diff)|)
Step 6: Threshold = median + k × MAD (k=3 by default)
Step 7: Return highest peak where gap to next peak ≤ threshold

Intuition: Real peaks form a smooth distribution. An outlier creates an abnormally large gap to the next peak. The algorithm finds the highest peak that 'fits' with the rest of the distribution.

A.3 Derivative Calculation

Central Difference Method

Velocity: $v[i] = (\theta[i+1] - \theta[i-1]) / (2\Delta t)$
Acceleration: $a[i] = (v[i+1] - v[i-1]) / (2\Delta t)$
Jerk: $j[i] = (a[i+1] - a[i-1]) / (2\Delta t)$

Why Central Difference?

- Second-order accuracy: Error $\propto \Delta t^2$ (vs. Δt for forward difference)
- Symmetric: No systematic lead or lag in timing
- Noise Handling: Less amplification than higher-order methods

Progressive Smoothing Strategy: Each differentiation doubles noise power. We apply progressively stronger smoothing: angle (6 Hz Butterworth) → velocity (+5-pt MA) → acceleration (+7-pt MA) → jerk (+9-pt MA).

A.4 Movement Phase Detection

Phase detection segments continuous data into meaningful movement epochs.

Concentric/Eccentric Phase Detection

- Based on velocity sign: Positive velocity = flexion (eccentric loading)
- Negative velocity = extension (concentric propulsion)
- Zero-crossing detection on smoothed velocity signal
- Minimum phase duration filter (50 ms) rejects noise-induced false transitions

Ground Contact Detection (Jump/Hop)

- Landing: Rapid transition from near-zero velocity to large negative velocity
- Contact: Period of high-frequency oscillation as limb absorbs impact
- Takeoff: Rapid transition from near-zero to large positive velocity
- Thresholds adaptive to signal amplitude (% of peak velocity)

Gait Cycle Detection

- Heel strike: Local minimum in knee angle (full extension)
- Toe-off: Velocity sign change following stance-phase flexion
- Stride = heel strike to next ipsilateral heel strike

A.5 Cross-Correlation & Temporal Lag

Cross-correlation measures similarity between two signals as a function of time offset.

Normalized Cross-Correlation

$r(\tau) = \Sigma[L(t) \times R(t+\tau)] / \sqrt{[\Sigma(L^2) \times \Sigma(R^2)]}$

- Computed across lag range $\tau = \pm 50\%$ of signal length
- Peak correlation value = waveform similarity (0–1)
- Lag at peak = temporal offset between limbs (ms)

Phase Offset Calculation

Phase (°) = (lag / period) × 360°

- 0° = in-phase (bilateral squat)
- 180° = anti-phase (walking gait)
- Used for movement classification and algorithm selection

A.6 Convolution-Based Real Asymmetry

Problem: Simple asymmetry (|L−R|/mean) is confounded by phase differences. Two identical signals with a timing offset appear asymmetric.

Solution: Convolution Decomposition

The convolution of a signal with itself (auto-convolution) captures its energy distribution independent of phase. By comparing auto-convolutions with cross-convolution, we isolate true magnitude differences.

Algorithm:

1. Compute auto-convolutions: $L \circledast L$ and $R \circledast R$
2. Compute cross-convolution: $L \circledast R$
3. Symmetric component = $(L \circledast R + R \circledast L) / 2$
4. Total energy = $(L \circledast L + R \circledast R) / 2$

5. Asymmetric energy = Total − Symmetric
6. Real Asymmetry (%) = (Asymmetric / Total) × 100

Clinical Advantage: Identifies genuine limb differences even when movement timing differs. More predictive of clinical outcomes than simple asymmetry for dynamic tasks.

A.7 Smoothness Metrics (SPARC & LDLJ)

SPARC (Spectral Arc Length)

Smooth movement has a simple frequency spectrum (single peak). Jerky movement has complex spectrum (multiple peaks, harmonics).

1. Compute FFT of velocity signal
2. Normalize magnitude spectrum to peak = 1
3. Calculate arc length: $SPARC = -\int\sqrt{(1/\omega c)^2 + (d\hat{V}/d\omega)^2}\, d\omega$
4. Integrate up to cutoff (10 Hz) or amplitude threshold (5%)
5. Negative sign: less negative = smoother

LDLJ (Log Dimensionless Jerk)

Integrates squared jerk, then normalizes to remove duration and amplitude dependence.

1. Compute jerk = $d^3\theta/dt^3$
2. Integrate squared jerk: $\int jerk^2\, dt$
3. Dimensionless normalization: × ($duration^5$ / $amplitude^2$)
4. Log transform: LDLJ = −ln(result)

Why Both? SPARC (frequency domain) and LDLJ (time domain) capture different aspects of smoothness. Concordance strengthens confidence; discordance suggests specific mechanisms.

A.8 Signal Processing Summary Table

Processing Step	Method	Purpose
Noise Removal	Butterworth 4th order, 6-10 Hz	Remove sensor noise, preserve movement
Differentiation	Central difference	Compute velocity, acceleration, jerk
Derivative Smoothing	Moving average (5-9 pt)	Reduce noise amplification
Peak Detection	Median + k×MAD threshold	Reject outliers, find plausible peaks
Phase Detection	Velocity zero-crossing	Segment concentric/eccentric phases
Bilateral Alignment	Cross-correlation	Find temporal lag, waveform similarity
True Asymmetry	Convolution decomposition	Separate phase from magnitude asymmetry
Smoothness (freq)	FFT + arc length (SPARC)	Spectral complexity of movement
Smoothness (time)	Integrated jerk² (LDLJ)	Temporal jerk accumulation