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Vision-Based Gait Analysis for Early Detection of Fall Risk in Elderly Patients with Musculoskeletal Disorders: A Deep Learning Approach

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Abstract:

Falls among elderly patients with musculoskeletal disorders represent a leading cause of injury-related hospitalization, disability, and mortality worldwide, with approximately 30% of community-dwelling adults aged 65 and older experiencing at least one fall annually. Current fall risk assessment methods including questionnaires, clinical rating scales, and instrumented walkway tests are limited by subjectivity, low sensitivity, and requirement for specialized equipment or personnel. This paper presents FallNet, a novel deep learning-based vision system for automated, non-contact gait analysis and fall risk prediction in elderly patients with musculoskeletal disorders. The framework processes monocular video from standard RGB cameras (smartphone or webcam) to extract 3D skeletal keypoints using a lightweight pose estimation backbone (MediaPipe or BlazePose), then computes a comprehensive set of 24 spatiotemporal and kinematic gait parameters including stride length, step time variability, gait speed, double support time, arm swing asymmetry, and joint angle trajectories. These features feed into a multi-scale temporal convolutional network (MS-TCN) with attention mechanism that classifies fall risk into three categories (low, moderate, high) and predicts prospective falls over a 12-month horizon. We validate FallNet on a prospective cohort of 342 elderly patients (mean age 74.6 ± 7.8 years, 62% female) with diagnosed musculoskeletal disorders (osteoarthritis, osteoporosis, sarcopenia, lumbar spinal stenosis) recruited from two geriatric outpatient clinics. Patients performed a standardized 10-meter walk test while being recorded by a single RGB camera, with concurrent 3D motion capture (gold standard) and 12-month prospective fall diary. FallNet achieves 89.4% accuracy in three-class fall risk classification (sensitivity 91.2%, specificity 88.1%, AUC-ROC 0.94) and predicts prospective falls with F1-score of 0.87, substantially outperforming clinical scales (Timed Up and Go: 68.3% accuracy; Berg Balance Scale: 71.2% accuracy; $p<0.001$ for all comparisons). Key gait parameters predicting fall risk include: gait speed <0.8 m/s (odds ratio 4.2), stride time variability >5% (OR 3.8), double support percentage >25% (OR 3.5), and arm swing asymmetry >30% (OR 3.1). The system runs in real-time (25 FPS on smartphone CPU) and requires no specialized equipment, making it suitable for deployment in primary care clinics, rehabilitation centers, and home settings. Explainable AI techniques (Grad-CAM and SHAP) identify which gait phases and body segments contribute most to fall risk decisions, enhancing clinical interpretability. This work establishes that vision-based deep learning gait analysis can provide accurate, accessible, and objective fall risk screening in elderly patients with musculoskeletal disorders, enabling early intervention and fall prevention strategies.

Key words: gait analysis; fall risk prediction; deep learning; elderly patients; musculoskeletal disorders; pose estimation; temporal convolutional networks;computer vision.

Introduction:

1.1 The Burden of Falls in Elderly Musculoskeletal Patients:

Falls are the second leading cause of accidental injury deaths worldwide, with an estimated 684,000 fatal falls annually. Among elderly individuals with musculoskeletal disorders including osteoarthritis, osteoporosis, sarcopenia, and spinal stenosis fall risk is amplified two- to four-fold compared

to age-matched healthy peers. Osteoarthritis impairs joint proprioception and range of motion; osteoporosis increases fracture susceptibility; sarcopenia reduces muscle strength and power; and spinal stenosis compromises balance and proprioception. The convergence of aging-related physiological decline with musculoskeletal pathology creates a high-risk population where early detection of fall risk is paramount [1-35].
Current clinical practice relies on subjective questionnaires (e.g., Falls Efficacy Scale), performance-based tests (Timed Up and Go, Berg Balance Scale, 10-meter walk test), and instrumented gait analysis using pressure walkways or motion capture systems. However, these methods have significant limitations: subjective tests lack sensitivity; clinical scales require trained personnel and are time-consuming; instrumented systems are expensive ($40,000–100,000), non-portable, and unavailable in most primary care settings [36-54].

1.2 Vision-Based Gait Analysis as an Alternative:

Recent advances in deep learning-based pose estimation notably OpenPose, MediaPipe, BlazePose, and ViTPose enable accurate 3D skeletal tracking from monocular video using standard RGB cameras (smartphones, webcams). These methods achieve joint localization error of 2-4 cm, sufficient for clinical gait analysis. Vision-based systems offer three critical advantages: (1) accessibility any smartphone or computer camera can capture data; (2) affordability no specialized hardware required; (3) scalability automated analysis can be deployed at population scale [55-68].

1.3 Contributions

This paper presents Fall Net, a deep learning-based vision system for fall risk detection in elderly patients with musculoskeletal disorders. Contributions include:

- A lightweight pose estimation pipeline optimized for elderly gait with musculoskeletal pathology (handling assistive devices, abnormal postures) [69-76].
- A multi-scale temporal convolutional network (MS-TCN) with attention that extracts 24 interpretable gait parameters from video and classifies fall risk.
- Prospective validation on 342 elderly musculoskeletal patients with 12-month fall follow-up.
- Identification of key gait predictors specific to musculoskeletal disorders.
- Explainable AI outputs for clinical interpretability [77-89].

1.4 Paper Organization

Section 2 reviews related work. Section 3 describes the FallNet architecture. Section 4 presents experimental methodology. Section 5 reports results. Section 6 discusses clinical implications. Section 7 concludes.

2. Related Work

2.1 Clinical Fall Risk Assessment

The Timed Up and Go (TUG) test is the most widely used clinical fall risk screen, with a cutoff of ≥12 seconds indicating high risk (sensitivity ~70%, specificity ~70%). The Berg Balance Scale (BBS) provides more comprehensive assessment but requires 15-20 minutes to administer. The Functional Gait Assessment (FGA) includes walking tasks with head turns and obstacles. However, all these tests suffer from ceiling effects in high-functioning elderly and lack sensitivity for subtle gait impairments[90-95].

2.2 Instrumented Gait Analysis

Instrumented walkways (GAITRite) and 3D motion capture (Vicon, OptiTrack) provide gold-standard gait parameters including stride length, step time variability, double support percentage, and joint kinematics. Studies have established fall risk thresholds: gait speed <0.8 m/s (OR 2.5-4.5), stride time variability >5% (OR 3.0-5.0), double support >25% (OR 2.5-3.5). However, these systems are expensive, non-portable, and require specialized training[96-104].

2.3 Vision-Based Gait Analysis

Recent work has applied pose estimation to gait analysis. Several studies have validated that video-based gait parameters correlate strongly with instrumented systems (r=0.79-0.94). Deep learning models using pose sequences have achieved 80-85% accuracy in faller vs. non-faller classification. However, prior work has focused on community-dwelling elderly without specific musculoskeletal diagnoses; validation in musculoskeletal populations remains limited[105-123].

2.4 Research Gap

No prior study has: (1) validated vision-based gait analysis specifically in elderly patients with musculoskeletal disorders, (2) incorporated 12-month prospective fall outcomes, or (3) provided explainable AI outputs for clinical interpretation. FallNet addresses these gaps[124-133].

3. Fall Net Framework
3.1 System Overview

Fall Net processes monocular RGB video of a patient walking to produce: (1) 3D skeletal tracking, (2) 24 spatiotemporal gait parameters, (3) fall risk classification (low/moderate/high), and (4) 12-month fall probability. The pipeline comprises three stages: pose estimation, gait parameter extraction, and deep learning classification[134-153].

3.2 Pose Estimation Module

We employ MediaPipe Pose (Google) as the backbone, which detects 33 body landmarks including shoulders, elbows, wrists, hips, knees, ankles, and feet. MediaPipe achieves 30 FPS on smartphone CPU and 95% keypoint detection rate in elderly patients (including those using canes or walkers). For patients with severe gait abnormalities, we apply temporal smoothing (Kalman filter) and gap interpolation (cubic spline).

Output: Per-frame (x,y,z) coordinates of 33 landmarks at 30 FPS.

3.3 Gait Parameter Extraction

From the 3D skeletal trajectories, we compute 24 gait parameters across four domains:
Temporal parameters:

- Gait speed (m/s)
- Stride time (s) and stride time variability (coefficient of variation)
- Step time (s) and step time asymmetry
- Cadence (steps/minute)
- Double support percentage (both feet on ground)
- Single support percentage
- Stance/swing phase ratio

Spatial parameters:

- Stride length (m) and stride length asymmetry
- Step width (cm)
- Toe clearance (cm)
- Hip, knee, ankle range of motion (degrees)

Kinematic parameters:

- Pelvic tilt and rotation amplitude
- Trunk flexion angle
- Arm swing amplitude and asymmetry
- Head stability (angular velocity)

Derived indices:

- Gait Deviation Index (GDI)
- Gait Asymmetry Index (GAI)
- Harmonic ratio (smoothness)

3.4 Multi-Scale Temporal Convolutional Network (MS-TCN)

The MS-TCN architecture processes the 24-dimensional gait parameter time-series (typical duration 10-20 seconds) to classify fall risk. Design features:

- Three parallel convolutional branches with kernel sizes 3, 5, and 11 (capturing stride-to-stride, step-to-step, and gait cycle dynamics)
- Squeeze-and-excitation attention for channel-wise feature recalibration
- Temporal attention to identify critical gait phases (e.g., swing phase, double support)
- Global average pooling followed by softmax for three-class classification

Training: Cross-entropy loss with class weights (imbalanced: low risk 42%, moderate 38%, high 20%). Adam optimizer, learning rate 0.0005, batch size 64[154-169].

3.5 Explainable AI Module

Two complementary explanation methods:

Grad-CAM: Generates heatmaps showing which temporal regions (gait phases) most influence the classification decision.

SHAP: Computes contribution of each gait parameter to the individual patient's risk score.

Outputs are displayed in a clinician dashboard with color-coded risk indicators and actionable recommendations.

4. Experimental Methodology

4.1 Participants

We prospectively enrolled 342 elderly patients (age ≥65 years) with diagnosed musculoskeletal disorders from two geriatric outpatient clinics (2023-2025). Inclusion criteria: physician-diagnosed osteoarthritis (knee/hip), osteoporosis, sarcopenia (EWGSOP2 criteria), or lumbar spinal stenosis; ability to walk 10 meters independently (with assistive device if usual). Exclusion criteria: acute fracture, recent joint replacement (<6 months), severe cognitive impairment (MMSE <18), neurologic disorders (Parkinson's, stroke) [170-179].

Characteristic Value
Age (years, mean±SD) 74.6 ± 7.8
Sex (female, %) 62%
Primary musculoskeletal diagnosis (%)
— Knee osteoarthritis 38%
— Hip osteoarthritis 12%
— Osteoporosis 24%
— Sarcopenia 16%
— Lumbar spinal stenosis 10%
Assistive device use (%) 28%
History of falls in prior year (%) 41%
Timed Up and Go (seconds, mean±SD) 14.2 ± 5.6
Berg Balance Scale (mean±SD) 48.3 ± 8.4

Table 1: *Participant Demographics and Clinical Characteristics (N=342)*

4.2 Data Collection Protocol

Gait recording: Patients performed a 10-meter walk test at self-selected comfortable pace on a 15-meter straight walkway. Two synchronized RGB cameras captured sagittal and frontal views (30 FPS, 1080p). Concurrent 3D motion capture (12-camera Vicon, 100 Hz) and pressure walkway (GAITRite) provided gold-standard validation [180-194].

Fall follow-up: Monthly fall diaries for 12 months post-assessment, with telephone follow-up for missing entries. Fall defined as "unintentionally coming to rest on the ground or other lower level."

4.3 Gold Standards

- Gait parameters: Vicon + GAITRite (averaged across 3 trials)
- Fall risk classification: Consensus of two geriatricians using multifactorial assessment (clinical judgment, not used for model training)
- Prospective falls: Binary (≥1 fall vs. 0 falls) at 12 months

4.4 Baselines:

Baseline Description
TUG test Timed Up and Go ≥12 seconds
BBS Berg Balance Scale <45
FGA Functional Gait Assessment <22
Random Forest Non-deep learning on gait parameters
CNN-only Standard CNN without temporal attention

4.5 Validation

Leave-one-site-out cross-validation. Performance metrics: accuracy, sensitivity, specificity, AUC-ROC, F1-score, calibration curve.

5. Results:

5.1 Fall Risk Classification Performance

Model Accuracy Sensitivity Specificity AUC-ROC
TUG (≥12s) 68.3% 71.2% 66.8% 0.72
BBS (<45) 71.2% 73.5% 69.8% 0.74
FGA (<22) 69.8% 70.9% 69.1% 0.73
Random Forest (24 gait params) 78.4% 79.2% 77.9% 0.85
CNN-only 81.2% 82.5% 80.3% 0.88
Fall Net (proposed) 89.4% 91.2% 88.1% 0.94

Table 2: *Three-Class Fall Risk Classification Performance (Low/Moderate/High)*

Key finding: FallNet improves accuracy by 18 percentage points over the best clinical scale (TUG 68.3% → 89.4%).

5.2 Prospective Fall Prediction (12-Month)

Model F1-score Sensitivity Specificity PPV NPV
TUG 0.62 0.65 0.71 0.56 0.78
BBS 0.64 0.67 0.73 0.58 0.80
FallNet 0.87 0.88 0.86 0.79 0.92

Table 3: *Prediction of Prospective Falls (≥1 fall at 12 months, N=122 fallers)*

Fall Net correctly identified 107 of 122 patients who fell (87.7% sensitivity). False positive rate: 14%.

5.3 Key Gait Parameters Predicting Fall Risk

Gait Parameter Threshold Odds Ratio 95% CI p	**value**
Gait speed <0.8 m/s 4.2 2.8	6.3 <0.001
Stride time CV 5% 3.8 2.5	5.8 <0.001
Double support 25% 3.5 2.3	5.3 <0.001
Arm swing asymmetry 30% 3.1 2.0	4.8 <0.001
Toe clearance <3 cm 2.5 1.6	3.9 <0.001
Hip ROM (affected side) <40° 2.2 1.4	3.5 0.002

Table 4: *Top Gait Predictors of High Fall Risk (Multivariate Logistic Regression)*

Musculoskeletal-specific findings: In osteoarthritis patients, knee range of motion and gait speed were most predictive (OR 4.5). In sarcopenia patients, arm swing amplitude and cadence were most predictive (OR 3.9). In spinal stenosis patients, double support percentage and trunk flexion were most predictive (OR 4.1)[195-215].

5.4 Model Explainability: Grad-CAM Analysis

Grad-CAM heatmaps revealed that the model attends to specific gait phases depending on patient diagnosis:

- Osteoarthritis: Swing phase (impaired knee flexion)
- Sarcopenia: Arm swing and push-off phase
- Spinal stenosis: Double support and stance phase

This diagnostic-specific attention pattern enhances clinical credibility.

5.5 Real-Time Performance

Metric Value
Pose estimation FPS 28-32
Gait parameter extraction (per 10m walk) 0.8s
FallNet inference time 42ms
End-to-end latency (video → risk score) <2s
Model size (quantized) 14 MB

Table 5: *Computational Performance (Smartphone: iPhone 12, Webcam: 1080p @30fps)*

5.6 Comparison Across Musculoskeletal Diagnoses

Table 6: FallNet Performance by Primary Diagnosis

Diagnosis N Accuracy Sensitivity Specificity
Knee OA 130 91.5% 93.2% 90.1%
Hip OA 41 87.8% 89.4% 86.5%
Osteoporosis 82 88.9% 90.2% 87.9%
Sarcopenia 55 85.5% 87.3% 84.1%
Spinal stenosis 34 91.2% 92.8% 89.9%

Performance was slightly lower in sarcopenia (lower signal-to-noise due to generalized weakness) but remained clinically acceptable (>85%).

6. Discussion:

6.1 Principal Findings

Fall Net achieves high accuracy (89.4%) for fall risk classification in elderly patients with musculoskeletal disorders using only monocular video. Key gait parameters gait speed <0.8 m/s, stride time variability >5%, double support >25%, and arm swing asymmetry >30%—are strongly predictive of future falls, with odds ratios of 3-4. Prospective fall prediction (12-month) with F1-score of 0.87 substantially exceeds clinical scales. The system runs on standard smartphones, enabling low-cost, scalable fall risk screening[216-219].

6.2 Comparison with Previous Work

FallNet improves upon prior vision-based fall risk models (typical accuracy 80-85%) by 4-9 percentage points, likely due to: (1) validation on a specific high-risk population (musculoskeletal disorders), (2) inclusion of 24 interpretable gait parameters, (3) multi-scale temporal convolution capturing both stride-to-stride and intra-stride dynamics, and (4) attention mechanisms focusing on clinically relevant gait phases.

6.3 Clinical Implications

Primary care screening: A 30-second smartphone video during routine clinic visits could flag high-risk patients for comprehensive geriatric assessment.

Rehabilitation monitoring: Serial gait analysis can track response to physical therapy and guide treatment adjustments.

Telehealth integration: Remote self-capture by patients at home (using smartphone) enables fall risk monitoring without clinic visits.

Musculoskeletal-specific thresholds: The model's ability to weight parameters differently by diagnosis suggests potential for personalized fall prevention.

6.4 Limitations

First, the cohort was recruited from two academic geriatric clinics; generalizability to community primary care settings requires validation. Second, patients with severe cognitive impairment (MMSE <18) were excluded; fall risk in dementia patients remains unaddressed. Third, the 10-meter walk test requires a minimum clear walking path; home environments may not accommodate this. Fourth, assistive device use (canes, walkers) was present in 28% of patients; pose estimation accuracy is reduced but remains sufficient (87% keypoint detection). Fifth, prospective falls were self-reported by monthly diary, subject to recall bias.

6.5 Future Directions

Multi-site validation: Deploy FallNet across 10 primary care clinics (target N=1,500).

Continuous monitoring: Extend to short video clips (3-5 seconds) for passive in-home monitoring.

Fall imminence prediction: Predict falls within 7-14 days using daily gait self-capture.

Intervention targeting: Randomized trial of FallNet-guided fall prevention (e.g., targeted physical therapy vs. usual care).

Integration with electronic health records: Automated fall risk documentation and alerting.

Post-fall assessment: Video capture immediately after near-fall events to identify prodromal gait changes.

7. Conclusion:

Falls in elderly patients with musculoskeletal disorders are common, morbid, and often preventable yet current fall risk screening tools are subjective, insensitive, or require expensive equipment. This paper introduced FallNet, a deep learning-based vision system that extracts 24 spatiotemporal gait parameters from monocular video to classify fall risk and predict prospective falls. In a prospective cohort of 342 elderly musculoskeletal patients, FallNet achieved 89.4% three-class fall risk classification accuracy and F1-score of 0.87 for 12-month fall prediction substantially outperforming clinical scales (TUG 68.3%, BBS 71.2%). Key gait predictors included gait speed <0.8 m/s (OR 4.2), stride time variability >5% (OR 3.8), double support >25% (OR 3.5), and arm swing asymmetry >30% (OR 3.1). The system runs on standard smartphones in real-time, requires no specialized equipment, and provides explainable AI outputs for clinical interpretation.

As global populations age and musculoskeletal disorders become increasingly prevalent, scalable, accessible fall risk screening becomes a public health priority. FallNet demonstrates that vision-based deep learning can deliver accurate, low-cost fall risk assessment, enabling early intervention and fall prevention strategies for millions of elderly patients worldwide. Future work will focus on prospective validation, continuous home monitoring, and integration into clinical fall prevention programs.

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