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Artificial Intelligence and Wearable Sensor-Based Prediction of Upper-Limb Overuse Injuries in Wheelchair Para Athletes: Implications for Sports Physiotherapy

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Abstract: Upper-limb overuse pathology, particularly of the shoulder and wrist, is the leading cause of pain and impaired performance among wheelchair para athletes, arising from the paradox of using load-bearing joints originally suited for mobility rather than sustained propulsive force. Traditional clinical screening relies on intermittent, subjective assessment and laboratory-based biomechanical testing, both of which are poorly suited to capturing the cumulative, ecologically valid loading histories that precipitate overuse injury. Recent convergence of low-cost inertial measurement units (IMU), surface electromyography (EMG), and pushrim force sensors with machine learning (ML) and deep learning (DL) analytics has opened a pathway toward continuous, field-based injury risk surveillance. This review synthesises current evidence on artificial intelligence (AI)-based movement analysis and wearable sensor systems for predicting upper-limb overuse injury in wheelchair-dependent para athletes. We examine the epidemiological and biomechanical rationale for shoulder and wrist vulnerability, the sensor modalities and AI architectures reported in the literature, and the reported predictive performance of these systems, before discussing the translational implications for sports physiotherapy practice, including workload monitoring, technique correction, and early referral pathways. The review identifies persistent gaps — a scarcity of studies conducted specifically in wheelchair-sport (rather than able-bodied or activities-of-daily-living) populations, limited external validation, heterogeneous outcome definitions, and minimal integration into physiotherapist-facing clinical workflows — and proposes a research and implementation agenda to close them.

Keywords: Artificial intelligence, wearable sensors, wheelchair propulsion, upper-limb overuse injury, shoulder pain, machine learning, sports physiotherapy, Paralympic athletes

I. INTRODUCTION

Wheelchair sport has grown substantially in scope and competitiveness since its inclusion in the Paralympic programme, yet this growth has been paralleled by a well-documented burden of upper-limb overuse injury. Unlike ambulant athletes, wheelchair users depend on the shoulder, elbow, and wrist complex for both propulsion and the majority of activities of daily living, so that a training- or competition-related overuse injury does not merely limit sporting performance but threatens functional independence [1], [2]. Reported prevalence of shoulder pain among manual wheelchair users ranges as high as 70–80% across the lifespan, with wheelchair court-sport athletes (basketball, rugby, tennis) showing elevated rates linked to repetitive high-force propulsion, sprinting, and directional changes [2], [3]. Clinical assessment of this risk has traditionally relied on periodic physiotherapist screening, patient-reported pain indices such as the Wheelchair User's Shoulder Pain Index, and laboratory-based three-dimensional motion capture — approaches that are resource-intensive, episodic, and poorly suited to capturing the cumulative loading history that actually drives tissue overload [3], [4].

The convergence of low-cost, wireless wearable sensors — inertial measurement units (IMU), surface electromyography (EMG), and instrumented pushrim/force sensors — with artificial intelligence (AI) and machine learning (ML) analytics offers a plausible route toward continuous, ecologically valid, and individualised injury risk monitoring. This review synthesises the current evidence base on AI-based movement analysis and wearable sensor prediction of upper-limb overuse injury specifically in wheelchair para athletes, and considers what this evidence means for sports physiotherapy practice.

II. EPIDEMIOLOGY AND BIOMECHANICAL BASIS OF UPPER-LIMB OVERUSE

A. Injury Burden in Wheelchair Sport

Upper-extremity injuries dominate the injury profile of wheelchair-dependent Paralympic athletes, in contrast to the lower-limb predominance seen in ambulant sport, reflecting the athlete's reliance on the arms for both mobility and sport-specific tasks [5]. Shoulder impingement, rotator cuff tendinopathy, and carpal tunnel syndrome are the most frequently reported diagnoses, consistent with repetitive strain mechanisms rather than acute trauma [3].

B. Propulsion Biomechanics as a Causal Pathway

The handrim propulsion cycle imposes cyclical, high-magnitude glenohumeral joint loading during the push phase, compounded by muscular imbalance between overdeveloped internal rotators/adductors and comparatively weak external rotators and scapular stabilisers [6]. Scoping and systematic reviews of propulsion biomechanics report that wheelchair users with existing shoulder pain display shorter push angles, higher stroke frequency, greater peak forces, and reduced movement variability compared with pain-free users, although the field has not resolved whether these patterns are causal or compensatory [1], [4]. During competitive tasks such as sprinting, athletes exhibit significantly greater peak glenohumeral abduction, scapular internal rotation, and trunk flexion range relative to submaximal propulsion, and greater shoulder pain severity is associated with these altered kinematics [7], [8].

C. Sport-Specific Load Amplification

Court-sport wheelchair athletes are further exposed to collision loading, rapid acceleration, and turning manoeuvres superimposed on baseline propulsion demand, which several authors identify as a distinguishing risk factor relative to non-athletic manual wheelchair users [5], [9]. This sport-specific amplification is the central rationale for why injury-risk models trained on able-bodied or activities-of-daily-living populations may not transfer well to competitive wheelchair sport.

III. WEARABLE SENSOR TECHNOLOGIES FOR MOVEMENT MONITORING

A. Inertial Measurement Units

IMUs combining accelerometry and gyroscopy are the most widely deployed sensor modality, typically mounted on the wheelchair frame, wheel, and upper arm/forearm segments. IMU-derived signals allow reconstruction of propulsion temporal parameters (push duration, cadence, recovery duration) and have been used to classify wheelchair-related activities of daily living with high accuracy in free-living conditions [10], [11].

B. Surface Electromyography

EMG provides a more direct index of muscular effort and exertion than kinematic sensors alone, and has been combined with IMU data to estimate shoulder joint loading via neural-network models validated against musculoskeletal modelling outputs, with reported effort–load correlations supporting its use as a proxy for cumulative tissue stress [12], [10].

C. Instrumented Pushrims and Force Sensors

Force- and pressure-instrumented pushrims capture kinetic variables (peak force, rate of force rise, jerk) directly at the human–wheelchair interface. Recent work links the rate of rise and jerk of applied pushrim force to shoulder pain status, suggesting that kinetic — not only kinematic — variables carry independent predictive information [7], [8].

IV. ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING APPROACHES

A. Classical and Ensemble Machine Learning

Random forest, gradient-boosted trees (e.g., XGBoost), and support vector machine classifiers remain the most commonly reported approaches for structured, feature-engineered sensor data in the broader sports injury-prediction literature, consistently outperforming simple logistic regression baselines on accuracy, precision, and area-under-curve (AUC) metrics [13], [14].

B. Deep Learning and Sequence Models

Bidirectional long short-term memory (Bi-LSTM) networks trained on raw accelerometer, gyroscope, and EMG time series have achieved classification accuracies above 95% for wheelchair-related shoulder-loading activities, substantially outperforming single-sensor or hand-crafted feature approaches [11].

In the broader sports-injury literature, ensemble methods and deep architectures (CNN, LSTM, RNN) have been reported to achieve 85–97% accuracy across diverse injury-prediction tasks, and graph neural network and survival-model architectures (e.g., DeepHit) have recently been applied to time-to-injury forecasting with concordance indices around 0.76–0.83 [15], [16], [17].

C. Explainability and Multimodal Fusion

A growing subset of studies incorporate SHAP (Shapley Additive Explanations) values or attention mechanisms to render model outputs clinically interpretable, and multimodal fusion architectures combining imaging, biomechanical, and wearable data are emerging as a route to more comprehensive risk profiling, though these remain largely unvalidated in wheelchair-specific populations [18], [19].

V. SYNTHESIS OF CURRENT EVIDENCE

Table I summarises representative studies applying wearable sensing and AI/ML methods to wheelchair-related upper-limb loading and, more broadly, sports injury prediction. A consistent pattern emerges: methodological feasibility is well established — sensor-based activity and load classification routinely exceeds 90% accuracy — but direct, prospective prediction of clinically diagnosed overuse injury within competitive wheelchair-sport cohorts is rare. The majority of wheelchair-specific studies validate against surrogate outcomes (shoulder load, activity classification, pain indices) in able-bodied participants or activities-of-daily-living contexts rather than athlete populations [10], [11], [12].

TABLE I. Representative Studies on Wearable/AI Approaches to Wheelchair Upper-Limb Loading and Sports Injury Prediction

Study focus	Sensor / AI method	Key finding
Shoulder load estimation [12]	IMU(5)+EMG; neural net	Load correlated with musculoskeletal-model estimates
SL-ADL classification [11]	IMU+EMG; Bi-LSTM	98% accuracy; forearm sensor outperformed upper-arm alone
Free-living wheelchair ADL [10]	Body-worn IMU; neural net	Substantial-to-almost-perfect sensitivity/PPV in field
Task intensity [9]	Accelerometry; ML class.	Feasible classification of overuse-linked task intensity
Pushrim kinetics [8]	Instrumented pushrim; kinetic modelling	Force rate-of-rise/jerk associated with shoulder pain
General sports injury [13]	GPS/HRV/IMU; ensemble ML, CNN/LSTM	85–97% accuracy; rarely validated in para-athletes

VI. IMPLICATIONS FOR SPORTS PHYSIOTHERAPY

A. *Workload and Technique Monitoring*

For the treating physiotherapist, wearable-derived, AI-classified propulsion metrics (push angle, stroke frequency, peak force, jerk) offer an objective, session-by-session complement to subjective pain reporting, enabling earlier identification of technique drift that precedes symptom onset [4], [8].

B. *Individualised Load Management*

Because absolute training and competition volume cannot be meaningfully reduced in most wheelchair sports without compromising performance, AI-supported monitoring is better positioned to support individualised load periodisation and targeted rotator-cuff/scapular strengthening than to prescribe blanket volume restrictions [6], [17].

C. *Referral and Escalation Pathways*

Explainable-AI outputs (e.g., SHAP-ranked risk factors) could, in principle, support triage — flagging athletes whose sensor-derived risk profile warrants closer clinical review — but this application remains largely theoretical in wheelchair sport pending prospective validation against physiotherapist-diagnosed outcomes [18], [19].

VII. CHALLENGES AND LIMITATIONS OF THE CURRENT EVIDENCE

Several limitations recur across the reviewed literature. First, most wearable/AI studies validating shoulder-load or activity-classification models were conducted in able-bodied participants simulating wheelchair activities of daily living rather than in wheelchair-sport athletes, limiting ecological validity [10], [12]. Second, outcome definitions are heterogeneous — some studies predict activity type, others estimate joint load, and few directly predict clinician-diagnosed overuse pathology, making cross-study comparison difficult [11], [14]. Third, sample sizes in wheelchair-specific studies are typically small (often fewer than 20 participants), constraining the generalisability of trained models [10], [12]. Fourth, model performance frequently degrades substantially when sensor configurations are reduced (e.g., single-sensor versus multi-sensor arrays), raising practical questions about deployability outside controlled research settings [11]. Finally, data heterogeneity, limited external validation, and privacy/compliance concerns are recognised as unresolved barriers across the wider AI-and-wearables injury-prediction field, and apply with particular force to a comparatively small, heterogeneous population such as wheelchair para athletes [16], [19].

VIII. FUTURE DIRECTIONS

Priority areas for future research include: (i) prospective cohort studies conducted within competitive wheelchair-sport populations that link wearable-derived features directly to clinician-confirmed overuse diagnoses rather than surrogate load or activity outcomes; (ii) standardisation of sensor placement, sampling protocols, and outcome definitions to permit meta-analytic synthesis; (iii) development of explainable, physiotherapist-facing dashboards that translate model output into actionable clinical recommendations; and (iv) transfer-learning or federated-learning approaches capable of building robust models despite the inherently small and heterogeneous wheelchair-athlete population [15], [16], [19].

IX. CONCLUSION

Wearable sensor and AI/ML approaches have demonstrated strong technical feasibility for classifying wheelchair-related upper-limb activity and estimating joint load, and an adjacent, more mature body of sports-injury-prediction literature reports high classification accuracy across other athlete populations. However, direct, prospectively validated prediction of upper-limb overuse injury specifically within wheelchair para-athlete cohorts remains an emerging rather than established evidence base. For sports physiotherapists, current systems are best regarded as objective monitoring adjuncts to, rather than replacements for, clinical assessment, with the greatest near-term value in individualised workload management and early technique-based risk flagging.

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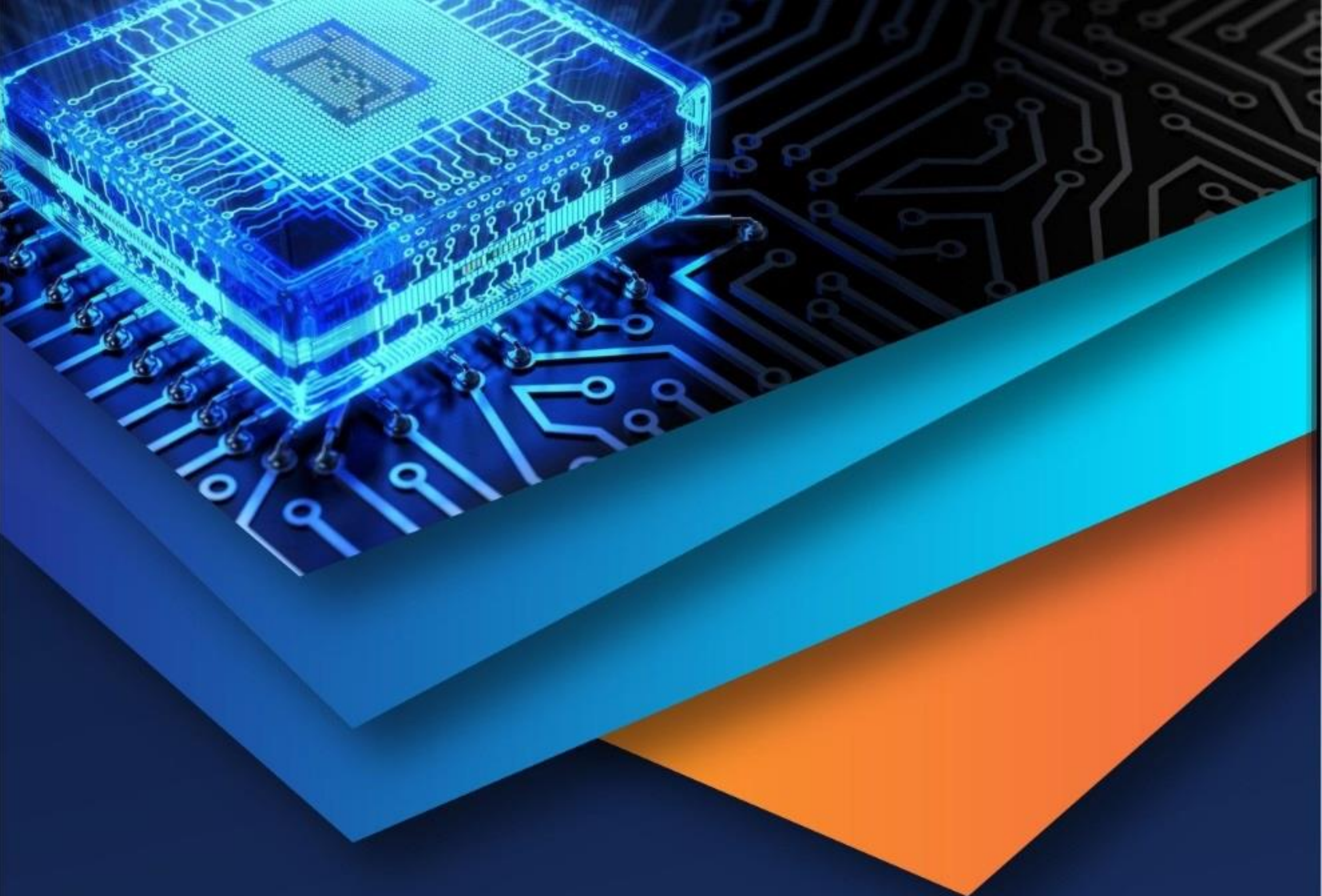

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