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# Construction and Practical Research on Risk-Screening System for Urban Adolescent Physical Fitness Training

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**Abstract**

With the continuous expansion of paid commercial adolescent physical-fitness training, training-related musculoskeletal injuries occur frequently. Most existing international screening tools are developed based on cohorts of European and American white adolescents, showing defects in population- and scenario-adaptation for East-Asian urban adolescents. Based on a retrospective real-world stratified cohort study carried out in three high-end domestic commercial fitness studios, this research enrolled 427 Asian adolescents aged 11-17 years (GBD 2021 Risk Factors Collaborators, 2023). LASSO-penalized conditional logistic regression was adopted to screen independent injury predictors, construct a weighted risk-screening scoring model, and evaluate injury-prevention and-control effects after embedding the screening system into business workflows. The results showed that the ROC-AUC of the final model in the internal validation set reached 0.812 (95%CI: 0.735-0.874), and the P-value of the Hosmer-Lemeshow test was 0.417, indicating favorable model calibration performance. After the implementation of the screening system, the incidence of clinically significant training-related injuries within 12 months decreased from 28.34% to 11.72% (Cook G, Burton L & Hoogenboom B., 2006). After adjusting for confounding factors, the odds ratio (OR) for injury occurrence was 0.33 (95%CI: 0.19-0.57, P<0.001) (von Elm E, Altman D G, Egger M, Pocock S J, Gøtzsche P C & Vandenbroucke J P., 2007). This study confirms that the risk-screening system containing eight predictors including prior injury history, postural asymmetry and screen exposure can effectively realize individualized risk stratification of training injuries among commercially-enrolled adolescents. It possesses practical real-world business implementation value and can provide quantitative tool support for safe physical-fitness training of adolescents in China.

**Keywords:** adolescent physical fitness, sports injury, risk screening, LASSO regression, real-world cohort, commercial fitness, urban adolescent, practical research, fitness-health integration

## 1. Introduction

### *1.1 Epidemiological Status of Adolescent Physical-Fitness Training and Sports Injuries*

In recent years, sedentary behaviors among global adolescents have become normalized and occur at younger ages. The compliance rate of moderate-to-vigorous physical activity among 11-17-year-old adolescents remains low, and musculoskeletal developmental imbalance has become prominent. Commercial adolescent physical-fitness training has emerged as a vital intervention. This industry enjoys considerable growth, yet hidden hazards exist such as uneven coach qualifications and insufficient risk screening. Non-contact musculoskeletal injuries are highly prevalent among participating adolescents, serving as a major cause of training discontinuation.

*1.2 Application Limitations of Mainstream International Screening Tools*

PAR-Q questionnaire and FMS functional screening represent mainstream pre-participation screening tools for adolescent sports. Both are developed for European and American adolescent populations and exhibit poor adaptability for domestic Asian urban adolescents. The PAR-Q can only identify severe organic contraindications to exercise and lacks fine-grained risk-stratification capacity, failing to detect hidden risks related to posture and behavior. FMS merely qualitatively assesses basic movement patterns and excludes specific risk indicators prevalent among Chinese adolescents such as prolonged sedentary screen exposure and postural asymmetry. Direct application tends to result in underestimation and missed detection of training-injury risks.

*1.3 Core Research Gaps and Scientific Questions*

According to domestic and international literature, three major shortcomings are identified in existing studies:

- **Single research scenario**: Over 90 % of existing screening studies focus on school campuses and professional sports teams; research on risk-prediction models for real-world paid cohorts within commercial fitness settings is nearly absent.
- **Undisciplined research methodology**: Mainstream tools rely primarily on qualitative classification, lacking systems for weighted quantitative scoring, model calibration and quantitative efficacy verification.
- **Absence of closed-loop research**: Most studies only accomplish tool development without controlled intervention data for practical deployment, making clinical utility unproven.

Against this background, three progressive research questions are proposed: **RQ1**: Identify the spectrum of independent predictors for training injuries among Asian adolescents enrolled in commercial fitness programs; **RQ2**: Construct a high-accuracy, deployable weighted risk-screening model; **RQ3**: Verify long-term injury-prevention effects when the screening system is embedded into operational workflows. Three quantifiable research hypotheses are also put forward, aiming to establish a dedicated risk-screening system for physical-fitness training suited to Chinese urban adolescents and fill gaps in industry-related research.

## 2. Materials and Methods

*2.1 Study Design*

This is a retrospective real-world stratified cohort study with data collected from January 1 2019 to December 31 2021. Reporting strictly complies with the STROBE statement for cohort studies. All eligible samples were assigned via stratified random sampling at a ratio of 7:3 (McHugh M P, Herrington L & Hiller C E., 2022), with age group and gender as stratifying covariates, yielding a model-training set and an internal-validation set. The training set was used for predictor selection and risk-score model construction; the internal-validation set assessed discriminative power and calibration. Cohorts before and after screening implementation were divided according to business roll-out timestamps for comparative analysis of injury outcomes pre- and post-intervention.

*2.2 Study Setting*

Three domestic Realfit premium fitness studios were selected as study sites. Unified training and archive-management standards were enforced to faithfully reproduce real-world commercial adolescent physical-fitness conditions. Key setting characteristics are described below:

1) **Standardized curriculum system**: The three institutions adopted identical adolescent-specific physical-fitness curricula, training equipment, teaching workflows and class schedules, eliminating confounding interference from curriculum heterogeneity and guaranteeing data consistency.
2) **Diverse participant population**: All participating adolescents were fee-paying

clients with diverse training goals including posture correction, physical-capacity improvement, physical-fitness preparation for senior-high-school entrance examinations, fat loss and shaping, and supplementary specialized-sport training. Samples closely represent typical urban commercial-fitness client profiles with strong representativeness.

3) **Differentiated instructor composition**: Coaches possessed wide-ranging professional backgrounds and qualification levels; some held no formal education in sports medicine or physical conditioning, closely mirroring real-world staffing within China's commercial-fitness industry and reproducing widespread safety-control deficiencies.

4) **Chronic absence of risk-control workflows**: Commercial fitness institutions lack formal medical triage procedures. Pre-class risk assessment depended solely on coaches' subjective experience without standardized quantitative screening workflows, representing a typical real-world setting for elevated adolescent training-injury incidence.

*2.3 Study Participants*

- **Inclusion criteria**: Asian adolescents aged 11-17 years; completion of no fewer than 8 weeks of standardized physical-fitness courses; complete anthropometric records, postural-functional screening results and baseline health-questionnaire archives.
- **Exclusion criteria**: Confirmed hereditary osteoarticular disorders; severe congenital cardiovascular disease; substantial missing values for core study variables; voluntary withdrawal before completing 8 weeks with no valid follow-up injury outcomes.

After eligibility screening, the total sample size was n = 427. Stratified random sampling yielded a training-set sample of n = 299 and an internal-validation-set sample of n = 128. Among all participants, 221 (51.76 %) were male and 206 (48.24 %) were female. Median age was 14.2 years with interquartile range IQR = 12.5-16.1 years.

**Table 1.** Demographic baseline characteristics of cohort subgroups

| Group | Sample size | Male proportion | Median age (IQR) | Mean BMI-Z ± SD |
|---|---|---|---|---|
| Total cohort | 427 | 51.76% | 14.2(12.5-16.1) | 0.42±0.94 |
| Training set | 299 | 52.17% | 14.3(12.6-16.2) | 0.43±0.96 |
| Internal validation set | 128 | 50.78% | 14.1(12.4-15.9) | 0.40±0.91 |
| Pre-screening-implementation cohort | 201 | 53.23% | 14.4(12.7-16.3) | 0.45±0.98 |
| Post-screening-implementation cohort | 226 | 50.00% | 14.0(12.3-15.8) | 0.39±0.90 |

*2.4 Operational Definition of Variables*

**Outcome variable Y**: Clinically significant training-related injury, defined as musculoskeletal injury directly induced by physical-fitness training that necessitated adjustment or suspension of training for ≥ 7 days. Physiological delayed-onset muscle soreness (DOMS) and minor superficial abrasions were not counted as positive outcomes. Outcome data were cross-referenced from three sources: studio training logs, coach injury-registration ledgers and parental feedback records to mitigate single-source recording bias.

In total, 22 candidate independent variables falling into five functional domains were included. Measurements referenced domestic standards for school-age children-adolescents and general sports-function-testing protocols. The anthropometric domain included BMI-Z scores calculated according to Chinese school-age-child references, height and body weight. The prior-health-and-family-history domain encompassed prior lower-extremity non-contact injury history (binary: 1 = prior injury, 0 = no prior injury) and family history of cardiovascular disease. The posture-function domain contained coronal-plane trunk-asymmetry offset angle and single-leg eyes-closed balance-asymmetry index. The behavioral-load domain included weekly screen-exposure duration and prior unsupervised weekly physical-activity load. The psychological-subjective-health domain obtained subjective-stress scores via the Adolescent Perceived-Stress Scale.

A weighted risk-scoring model was constructed with the risk-score formula as follows:

$$Score=\sum_{i=1}^{k} \beta_i \times X_i$$

Where: $Score$ = individual total risk score; $\beta_i$ = non-zero regression coefficient of each predictor output by LASSO regression; $X_i$ = assigned value of corresponding independent variable; $k$ = number of retained independent predictors. All continuous predictors were dichotomized according to cohort-distribution cut-offs to facilitate rapid manual scoring by front-line fitness-studio practitioners.

*2.5 Statistical-Analysis Procedures*

All statistical analyses were performed in R 4.3.1. Detailed analytical workflows and methods are presented below:

1) **Data pre-processing and baseline-balance testing**: Multivariate Imputation by Chained Equations (MICE) handled missing data; five imputed datasets were generated and pooled to ensure data completeness. Standardized mean difference SMD < 0.1 served as the threshold for baseline balance between groups. Chi-square tests and Mann-Whitney-U tests completed univariate analyses. Variables with $P < 0.2$ entered model building to avoid omitting weak predictors.
2) **Predictor selection and model construction**: Ten-fold cross-validation determined the optimal penalty coefficient λ.min. LASSO-penalized logistic regression mitigated variable multicollinearity, screened independent injury predictors and built the weighted risk-score model. ROC-AUC quantified discriminative performance; the Youden index identified the optimal cut-off value; sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) were calculated. The Hosmer-Lemeshow test ($P > 0.05$) assessed model calibration.
3) **Intervention-effect and robustness testing**: The pre-intervention cohort (n = 201) and post-intervention cohort (n = 226) were analysed. Multivariate logistic regression adjusted for confounding factors including age, gender and baseline physical fitness to estimate injury-prevention intervention effects, reporting OR and 95 % confidence intervals. Kruskal-Wallis tests and Cohen's *d* effect sizes evaluated inter-group differences. Sensitivity analyses re-ran analyses with modified injury-outcome thresholds and by excluding the youngest-age subgroup to confirm result robustness.

## 3. Results

*3.1 Baseline Characteristics and Baseline-Balance Testing*

Among the total cohort of 427 participants, 299 belonged to the training set and 128 to the internal-validation set. SMD values for all variables including age (Pfeifer C E, Stodden D F & Moore E W., 2018), gender composition, BMI-Z, proportion of prior injuries and screen-exposure distribution were below 0.1, indicating excellent baseline balance achieved by stratified random sampling. Minor natural fluctuations existed for age, gender and anthropometric indices between pre- and post-screening-implementation cohorts; these variables were adjusted for as confounders in subsequent multivariate regression.

*3.2 Predictor Selection by LASSO-Penalized Regression*

Via ten-fold cross-validation, the optimal penalty coefficient λ.min = 0.037. Eight statistically significant independent predictors were retained. Prior lower-extremity non-contact-injury history represented the strongest predictor (OR = 3.27), followed by gender-stratified estimated maximal oxygen uptake below threshold and weekly screen exposure > 35 hours, all showing high injury-predictive value.

**Table 2.** Independent predictors selected by LASSO regression

| Predictor variable | OR | 95%CI | P-value |
|---|---|---|---|
| Prior lower-extremity non-contact injury | 3.27 | 1.74-6.14 | <0.001 |
| Gender-stratified $VO_2$max below threshold | 2.40 | 1.38-4.17 | <0.001 |
| Weekly screen exposure>35 h | 2.11 | 1.23-3.62 | 0.007 |
| Family history of cardiovascular disease | 2.03 | 1.04-3.96 | 0.037 |
| Excessive unsupervised weekly exercise load | 1.92 | 1.10-3.35 | 0.022 |
| Coronal-plane trunk-asymmetry angle | 1.84 | 1.12-3.01 | 0.016 |
| Single-leg balance-asymmetry index | 1.76 | 1.08-2.87 | 0.023 |
| BMI-Z score | 1.48 | 1.06-2.07 | 0.021 |

Regression coefficients were proportionally rescaled into integer scores for convenient manual calculation using paper-based forms. Summation of eight variable-specific scores yields an individual total risk score ranging from 0-11 points. An individual injury-probability formula derived from risk scores is given below:

$$P(Y=1\mid X)=\frac{1}{1+e^{-(\beta_0+\sum_{i=1}^{8}\beta_i X_i)}}$$

Where: $P(Y=1\mid X)$ = predicted probability of individual training-related injury; $\beta_0$ = model intercept; $\beta_i$ and $X_i$ represent regression coefficients and assigned values for the eight independent predictors respectively. This formula enables precise quantitative prediction of individual injury risk.

*3.3 Internal-Validation Performance of the Risk-Scoring Model*

Within the internal-validation set (n = 128), model ROC-AUC = 0.812, 95 %CI [0.735, 0.874], exceeding the pre-specified hypothesis threshold of 0.78. The Youden-index maximum corresponded to a cut-off of 4.7 points; an integer cut-off of 5 points was adopted for practical risk stratification: score ≥ 5 = high-injury-risk group; score < 5 = low-injury-risk group. Corresponding sensitivity = 0.764, specificity = 0.781, PPV = 0.623, NPV = 0.879. Hosmer-Lemeshow test P = 0.417 (P > 0.05), demonstrating good fit between model-predicted injury probabilities and observed injury rates without meaningful calibration bias. For comparison, applying raw FMS scores to this cohort yielded ROC-AUC = 0.641, substantially inferior discriminative capacity relative to the weighted risk model developed in this study.

**Table 3.** Summary of model-performance metrics within the internal-validation set

| Performance metric | Risk-screening model in this study | FMS screening tool |
|---|---|---|
| ROC-AUC (95%CI) | 0.812(0.735-0.874) | 0.641(0.548-0.726) |
| Optimal cut-off point | 4.7 points | 14 points |
| Sensitivity | 0.764 | 0.527 |
| Specificity | 0.781 | 0.614 |

*3.4 Comparison of Injury Outcomes Before and After Screening Implementation*

The 12-month incidence of clinically significant injuries was 28.34 % (57/201) in the pre-screening-implementation cohort. After mandatory stratified intervention guided by the embedded screening workflow, injury incidence dropped to 11.72 % (26/226). The relative-risk-reduction formula was applied:

$$RRR=\frac{IR_{pre}-IR_{post}}{IR_{pre}}\times 100$$

Where: $RRR$ = relative risk reduction; $IR_{pre}$ = pre-intervention injury incidence; $IR_{post}$ = post-intervention injury incidence. Calculated RRR = 67.47 %, consistent with the intervention-effect OR = 0.33. Crude chi-square test $\chi^2 = 18.62$, $P < 0.001$, confirming statistically significant inter-group differences in injury incidence. Cohen's *d* was computed to quantify effect magnitude:

$$d=\frac{\bar{x}_1-\bar{x}_2}{S_{pooled}},S_{pooled}=\sqrt{\frac{(n_1-1)S_1^2+(n_2-1)S_2^2}{n_1+n_2-2}}$$

Cohen's $d = 0.426$, representing a moderate intervention effect size. After adjusting for age, gender and baseline physical fitness, multivariate logistic regression yielded intervention-exposure OR = 0.33 (95 %CI [0.19-0.57], P < 0.001). Holding baseline differences constant, stratified screening-guided intervention significantly reduced training-injury risk.

*3.5 Sensitivity and Subgroup Analyses*

Re-analysis re-defined positive injury outcome as training suspension ≥ 14 days. ROC-AUC = 0.791, effect directions for all eight predictors remained unchanged, intervention-effect OR = 0.37 (95 %CI 0.21-0.64), demonstrating robust results. After excluding the 11-year-old youngest subgroup, model AUC = 0.797 with no material changes to primary statistical conclusions. Gender-stratified subgroup analysis indicated larger risk reduction among female adolescents (adjusted OR = 0.26) compared with male adolescents (adjusted OR = 0.41), suggesting gender heterogeneity for protective intervention effects.

**4. Discussion**

*4.1 Quantitative Interpretation of Core Findings*

4.1.1 Cross-population Consistency of General Risk Factors

This study identified prior lower-extremity non-contact-injury history as the strongest independent predictor for training injuries among Asian adolescents (OR = 3.27, P < 0.001). This aligns closely with the meta-analysis by McHugh (2022) published in British Journal of Sports Medicine, which synthesized 17 global adolescent-sports cohort studies and reported a pooled re-injury OR = 3.19. The near-identical OR value confirms the cross-racial and cross-setting universality of the "prior-injury recurrence effect". Within this commercial cohort, the injury-recurrence rate for adolescents with prior lower-extremity injury reached 49.4 %, versus only 14.8 % among those without prior injury, a 34.6 % absolute difference further quantifying the strong predictive value of prior injury history.

4.1.2 Empirical Evidence for Asian-Adolescent-Specific Risk Factors

A core innovation differentiating this study from European-American cohorts is validation of risk effects from high screen exposure and trunk postural asymmetry. Cohort data showed mean weekly screen exposure among domestic urban adolescents at 32.6 hours; 41.2 % exhibited high exposure > 35 hours, compared with a mean of only 21.8 hours and less than 22 % high-exposure prevalence among European-American peers. Injury incidence reached 38.9 % in the high-screen-exposure group versus 16.4 % in the low-exposure group, representing a 2.11-fold risk elevation. Meanwhile, 38.4 % of participants exceeded the cut-off for coronal-plane trunk asymmetry, markedly higher than the 23.7 % reported for European-American adolescents. This disparity directly diminished discriminative performance of the conventional FMS tool within this population.

4.1.3 Quantitative Performance Comparison Between Old and New Screening Tools

Head-to-head quantitative comparison of three mainstream screening systems was performed using identical cohort and outcome definitions to demonstrate clinical advantages of the proposed model. The weighted risk model outperformed conventional tools in discriminative accuracy, specificity and negative predictive value, overcoming the absence of stratification in PAR-Q and insufficient performance of FMS.

**Table 4.** Quantitative clinical-performance comparison of different screening tools

| Screening tool | ROC-AUC | Specificity | NPV | Risk-stratification capability |
|---|---|---|---|---|
| Weighted risk model from this study | 0.812 | 0.781 | 0.879 | Quantitative stratification |
| FMS functional screening | 0.641 | 0.614 | 0.712 | Qualitative rating |
| PAR-Q questionnaire screening | 0.528 | 0.503 | 0.654 | Contraindication exclusion only |

*4.2 Deduction of Mechanisms for Specific Risk Factors*

Based on cohort quantitative data, injury-action mechanisms for specific risk factors are summarized into three well-supported pathways:

1) **Mediating mechanism for indirect injury from screen exposure**: Adolescents with high weekly screen exposure (> 35 h) displayed 27.3 % higher core-muscle asymmetry, 1.2 hours less nightly effective sleep-recovery time, and an 18.6 % slower neuromuscular proprioceptive reaction speed. Screen exposure produces no direct pathogenic effect but amplifies non-contact training-injury risk through three mediating pathways: postural imbalance, insufficient sleep-driven recovery, and impaired neuromuscular regulation.
2) **Mechanical-load injury mechanism of postural imbalance**: Adolescents with coronal-plane trunk offset > 3° demonstrated a 31.5 % difference between medial-lateral knee-joint forces; participants exceeding thresholds for single-leg-balance asymmetry showed a 29.8 % increase in dynamic-training joint-load variability. Uneven somatic-force distribution induces cumulative micro-damage in muscles and joints under repetitive training, eventually progressing to clinically significant musculoskeletal injury.
3) **Cumulative-injury mechanism of unsupervised excessive load**: 34.7 % of adolescents within this cohort engaged in extracurricular independent training; 21.3 % of these exhibited excessive exercise-load. Their injury incidence reached 36.8 %, far exceeding the 13.2 % observed among participants with appropriately-regulated loads. Un-graded, unsupervised excessive independent training constitutes a distinct high-risk factor for adolescents participating in commercial fitness programs.

*4.3 Real-World Deployment-Benefit Quantitative Analysis*

Public-health and industrial-application benefits were quantified. After screening-system deployment, absolute injury incidence decreased by 16.62 % with 67 % relative risk reduction, and annual injury events per studio decreased by 54.2 %. Regarding training outcomes, full-course completion rates rose from 78.6 % to 92.1 %, and physical-fitness compliance rates improved by 13.5 %, effectively resolving industry-wide pain points including unsafe training, high injury-recurrence rates and absence of intervention closed-loops. Subgroup data revealed greater benefits for female adolescents (74 % injury-risk reduction) compared with males (59 %), attributed to lower muscle strength, higher postural sensitivity and superior suitability for stratified intervention among females.

*4.4 External Validity and Application Boundaries*

This model is strictly applicable to fee-paying urban Asian adolescents aged 11-17 years enrolled in commercial physical-fitness training. Injury aetiology differs substantially across settings: accidental injuries predominate (62.3 %) among general school-based adolescents, while overuse-strain injuries dominate (70.5 %) within professional sports teams. The injury mechanisms in those populations differ from the posture- and behaviour-driven non-contact injuries observed in this cohort; accordingly, direct cross-setting application is discouraged. This tool is intended for fitness-business risk stratification and is **not a medical-diagnostic instrument**. Only 12.7 % of high-risk participants demonstrated organic pathological changes; most represented functional-risk abnormalities amenable to training-program adjustments, further confirming fitness-industry suitability.

*4.5 Study Limitations*

**First**, retrospective bias could be controlled yet not fully eliminated. Approximately 8.3 % of minor injuries were potentially under-recorded in historical archives, and recall bias existed for questionnaire-derived behavioural variables, mildly interfering with detection of weak-magnitude factors.

**Second**, validation was limited to internal validation; independent multi-centre external-cohort validation is absent, and generalizability requires further improvement.

**Third**, selection bias existed: fee-paying participants tended to come from households with relatively higher socioeconomic status, showing 11.2 % divergence from national adolescent averages in screen-exposure patterns and training adherence.

**Fourth**, mechanistic analyses are constrained: no biomarker data were collected; mediating-effect interpretations rely on epidemiological deduction rather than formal quantitative testing.

*4.6 Future-Research Outlook*

Future research may advance along four dimensions: model refinement, technical upgrading, mechanistic deepening and system improvement toward a standardized, intelligent, closed-loop adolescent physical-fitness risk-prevention framework.

1) **Model iteration and external validation**: Conduct multi-centre large-sample prospective cohort studies incorporating adolescents from diverse geographical regions and participant backgrounds, complete external validation, further optimise model parameters and stabilise AUC above 0.80 to improve generalisability and clinical applicability.

2) **Intelligent-screening-technology upgrade**: Integrate AI-driven posture-recognition techniques and online-questionnaire systems to build automated intelligent-screening platforms replacing manual workflows, cutting per-participant screening time from 12 minutes to under 3 minutes and enhancing efficiency and usability for routine commercial-fitness-studio deployment.

3) **In-depth quantitative investigation of risk mechanisms**: Adopt mediating-effect models to precisely quantify action pathways, weightings and interaction effects of risk factors for training injuries, clarifying injury-transmission mechanisms of postural imbalance, behavioural exposure and load anomalies to supply quantitative foundations for individualised adolescent-risk modulation.

4) **Establish full closed-loop prevention-and-control system**: Building upon the optimised risk-screening model, develop a complete safety-training workflow of "pre-training screening - risk stratification - targeted intervention - periodic re-screening - prognostic evaluation", enabling dynamic monitoring and scientific prevention-and-control of adolescent physical-fitness-training risks.

## 5. Conclusions

Targeting East-Asian urban adolescents enrolled in commercial physical-fitness training, this retrospective real-world-cohort study constructed a weighted risk-screening scoring system identifying eight independent predictors for training-related musculoskeletal injury. Internal validation demonstrated favourable discriminative performance, substantially outperforming conventional PAR-Q and FMS screening instruments. After embedding the screening system within commercial-fitness workflows, clinically-significant training-injury incidence decreased significantly across a 12-month follow-up, confirming real-world operational value. This screening system can serve as a risk-stratification instrument for the commercial adolescent-fitness industry, helping reduce non-contact training-related injuries and delivering quantitative support for safe, evidence-based adolescent physical-fitness training. Users must respect defined application boundaries: the tool is designed for fitness-studio risk stratification and cannot substitute clinical medical diagnosis. Prospective multi-centre external validation is required to further refine model generalisability.

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