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Patellofemoral pain is associated with complex gait deviations captured by an artificial intelligence-derived gait index

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Abstract

Background: Patellofemoral pain (PFP) in active women is associated with gait adaptations. The Movement Deviation Profile (MDP) summarises deviations in multi-segment kinematic deviation, but it is unclear how the magnitude of deviation relates to pain. We investigated the relationship between MDP and pain intensity during walking.

Methods: In a retrospective, laboratory-based study, we analysed three-dimensional gait data from women with PFP (n = 571) alongside matched asymptomatic controls for reference modelling. Pain intensity was rated on a 0–10 visual analogue scale (VAS). Typical gait was defined from controls; Euclidean distances across 13 kinematic curves yielded the mean MDP (MDP_{mean}). We used linear regression, and the results remained consistent after controlling for the year of data collection and addressing heteroskedasticity in the standard errors.

Findings: In women with PFP, the mean MDP was 13.17° (95% CI: 12.93°–13.41°), and the mean VAS was 6.03 (95% CI: 5.91–6.15). Each 1-point increase in VAS corresponded to an approximately 1.99° increase in MDP_{mean} (R^2=0.92). This relationship remained consistent even after adjusting for the year (β = 1.98°; 95% CI: 1.93–2.04; $p < 0.001$), suggesting that changes over time did not influence the observed association.

Interpretation: In women with PFP, higher pain intensity is closely linked to more significant gait deviations, underlining the clinical importance of MDP as a quick measure of movement change. Although the retrospective nature prevents causal conclusions, the strength and consistency of the link indicate that pain level can serve as a useful marker for kinematic deviations during gait analysis.

Keywords: Patellofemoral pain, Movement Deviation Profile, Gait analysis, Joint kinematics

Introduction

Patellofemoral pain (PFP) is one of the most common musculoskeletal conditions and a leading cause of knee pain, with annual prevalence estimates around 22% in adults and higher rates in women (29.2%), highlighting its clinical significance [1]. Beyond measurable physical impairments, pain itself causes disability, limits daily activities and altered movement patterns [2–4]. Although numerical pain scales classify scores of 0–3 as mild, 4–7 as moderate, and 8–10 as severe, these thresholds often fail to predict which patients will have meaningful functional decline [5]. What remains uncertain and a key knowledge gap is whether, and how much, the intensity of pain relates to measurable deviations in gait patterns in women with PFP. Given evidence that standard biomechanical or strength metrics alone do not fully explain pain or functional limitations in this population, clarifying the pain–gait connection may help improve assessment and guide more targeted rehabilitation strategies [4,6].

Clinically, pain produces a broad spectrum of motor adaptations, ranging from subtle motor compensations during task execution to the complete avoidance of painful movements [5, 7]. Furthermore, women with PFP tend to avoid weight-bearing activities, and while the evidence supporting associated kinematic changes is considered limited (low to moderate), mainly due to the type of study designs, these findings still offer meaningful insights relative to asymptomatic females [8].

There are known associations between pain and observed movement variations during gait in individuals with PFP [9], specifically reduced walking speed with a lower cadence, shorter stride length, a greater contralateral pelvic drop, less knee flexion and consequently a lower internal knee extensor moment [8].

Indexes based on biomechanical variables assist in interpreting data from kinetic and three-dimensional kinematic analyses. Due to the numerous biological variables and their complex interactions, it is essential to implement data reduction strategies that preserve meaningful information rather than analyzing multiple parameters separately, as is common in clinical gait analysis [10]. Various gait indexes evaluate deviations in patients atypical walking patterns compared to a control group. The aim is to reduce the volume and complexity of data collected during three-dimensional gait analysis.

Gait indexes are commonly used in neurological patients [11], but their application to individuals with musculoskeletal disorders is limited [12]. Our previous research employed the Movement Deviation Profile (MDP) to compare the kinematics of women with PFP to those of asymptomatic women during various activities [13]. The MDP offers a reliable way to

summarise and simplify complex kinematic data [14], by comparing gait patterns to typical data while incorporating more robust statistical features [15]. It utilises a self-organising map (SOM), an unsupervised machine learning technique, to reduce complex kinematic data into lower-dimensional representations. A single summary measure, the MDP_{mean}, indicates how far a group is from a reference control group. A systematic review indicates that the MDP is a more effective approach than other gait analysis indices [15].

Recent studies indicate that pain intensity may influence kinematic and kinetic parameters [16-19]. Specifically, during clinical and biomechanical assessments, women with patellofemoral pain (PFP) experiencing different pain levels may adopt various movement strategies [17]. A patellofemoral joint (PFJ) loading protocol was found to be an effective method for exacerbating the pain [20]. After PFJ loading, patients with PFP reported higher pain levels and increased vertical loading rates [16]. Additionally, pain worsening led to a rise in peak dynamic knee valgus during single-leg squats [17], greater rear foot eversion, and asymmetry in forefoot plantar pressure during overhead and double-leg squats [21]. Despite these findings, a gap remains in the literature regarding how pain intensity relates to alterations in gait deviations.

Prior work has related PFP pain to numerous biomechanical alterations, but interrogating variables one by one is impractical and prone to selective emphasis. We therefore adopt a strategy analysis that synthesises all variables into one number, the MDP. It condenses multi-segment, time-normalised waveforms into a single deviation score (MDP_{mean}) referenced to typical gait. It enables an unbiased, feasible test of the pain–gait association in women with PFP. By design, this cross-sectional analysis does not prescribe a rehabilitation target nor adjudicate directionality. Pain may drive compensatory movement, altered movement may amplify pain, or both may interact bidirectionally. Notably, prospective evidence in related domains suggests that fear of movement can arise after symptom onset [6]. However, whether an analogous temporal ordering applies to gait deviations remains unknown. Thus, we aim to determine whether pain intensity covaries with MDP_{mean} during walking, providing a clinically interpretable benchmark and a hypothesis-generating basis for future causal trials. We hypothesise that higher pain scores will correspond to greater departures from typical gait patterns.

Methods

Study design

A retrospective cohort study was designed, approved by the local ethics committee and conducted in a human movement laboratory (protocol number 1.912.221). This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) [22].

Participants

Between 2012 and 2020, 571 female volunteers diagnosed with PFP and 571 matched asymptomatic female participants, based on age, height, and weight, who served as a reference gait control group, were selected from the laboratory's database.

All participants provided informed consent before data collection. They met the same clinical criteria and followed the same biomechanical data collection protocols. All participants with PFP were diagnosed by physiotherapists specialised in musculoskeletal assessment, each with at least five years of experience in lower limb disorders and previously trained by the same supervisor. Both groups comprised women aged 18 to 35 years who engaged in physical activity for at least 20 minutes three times a week. PFP participants experienced retropatellar and/or peripatellar pain for a minimum duration of three months, with a pain intensity rating of at least 3 on a Visual Analogue Scale (VAS) [23] and reported pain during at least two of the following activities: prolonged sitting, stair climbing, squatting, running, or jumping [24].

Exclusion criteria for PFP subjects included a history of lower limb or spinal surgery, patellar dislocation, anterior knee pain resulting from trauma, coexisting knee joint conditions such as meniscal and/or ligament injuries, lateral and/or posterior knee pain, cardiovascular issues, or locomotion disorders that could affect assessment, pregnancy, and limb length discrepancy greater than 1 cm, as measured by a tape measure. Control participants were excluded if they reported any of these conditions.

Procedures

All participants who underwent the 3D gait assessment were subjected to the same procedures. Kinematic data were captured using a Vicon system (Vicon, Denver, CO) with 8 Bonita 10 cameras (sampling at 120 Hz). Thirty-six spherical retroreflective markers with a diameter of 14 mm were placed using double-sided tape. Markers were placed on the manubrium and xiphoid process of the sternum, spinous process of the 7th cervical vertebra, 10th thoracic vertebra, and right scapula. They were positioned bilaterally on the acromion, posterior and anterior iliac spine, upper lateral and anterior 1/3 surface of the thigh, femoral epicondyles, patella, upper lateral and both upper and lower anterior surfaces of the shank,

lateral malleolus, calcaneus, and the second metatarsal head. The marker set followed the Plug-in Gait model, a reliable and accurate tool for gait analysis [25,26]. Cameras were calibrated before each session.

Data collection was conducted after participants had a short familiarisation period, during which they walked freely around the laboratory. The volunteers walked barefoot along an eight-metre walkway at a self-selected speed, with six metres corresponding to the calibrated capture volume. Although some datasets also included other testing conditions, gait trials were always collected first, before any additional tasks. Each participant completed at least six consecutive gait trials without resting. All data were collected in the same laboratory, using an identical camera positioning and setup throughout the entire data collection period. Anthropometric measurements (i.e., height, mass, distance between the anterior superior iliac spines, width of knees and ankles, and length of lower limbs) were taken. The marker coordinates were captured, reconstructed in 3D and labelled according to the biomechanical model. A pilot study with the first 100 participants from this research observed an Intraclass Correlation Coefficient (ICC2, K) ranging from 0.79 to 0.98 and a Standard Error of Measurement (SEM) ranging from 0.27 to 2.20°. The checklist items are presented in the Supplementary Material, in line with previous recommendations [8].

Before gait data capture, PFP participants were asked to report the average pain, measured by VAS, they experienced over the last four weeks in a standardized manner. The VAS data were also retrieved from our laboratory database.

Data Analysis

Processing

All the 3D marker trajectories were further reprocessed using Vicon Nexus 2.14 software to estimate the joint centres and to ensure consistency in methodology across all data collected. Gait cycles were identified using algorithms that predict initial contact and toe-off events based on the method described by Zeni Jr. et al. (2008) [27]. A Woltring filter with a two mean squared error (2 MSE) was applied to minimize vibration noise in the marker trajectories caused by soft tissue movement. Six gait cycles per participant were selected for analysis, performing a total of 3,426 gait cycles. The angles in the frontal, sagittal, and transverse planes of the trunk and pelvis segments relative to the laboratory, the frontal, sagittal, and transverse planes of the thigh relative to the pelvis, the frontal and sagittal planes of the

shank relative to the thigh, the sagittal plane of the foot relative to the shank, and the absolute transverse plane of the foot in relation to the laboratory were calculated.

Movement Deviation Profile

The MDP simplifies and summarises kinematic data using a SOM [28], an unsupervised machine-learning technique that generates a low-dimensional representation of a high-dimensional dataset while preserving most of the informational content [14]. In this study, the MDP quantifies the deviation in the gait of individuals with PFP relative to gait normality, comprising 571 control female volunteers. For the calculation of the MDP, the following kinematic data were considered: pelvis (anterior/posterior tilt, upward/downward obliquity and internal/external rotation), hip (flexion/extension, abduction/adduction and internal/external rotation), knee (flexion/extension and valgus/varus), ankle (dorsiflexion/plantarflexion), foot (internal/external rotation), and trunk (anterior/posterior tilt, upward/downward obliquity and internal/external rotation).

A combined set of 13 kinematic joint curves from the control database was used to train the neural network, establishing an operational definition of typical gait patterns. The same set of 13 kinematic curves for the PFP group was then presented to the trained SOM (Control and PFP joint curves for kinematics are provided in the supplementary section data). The neural network's performance metric was then utilized to quantify deviations in the PFP group from normality. The MDP is the multidimensional Euclidean distance between each PFP participant and gait normality, derived from the kinematics of the control group, generating a unique deviation curve (51 data points from 13 kinematic curves) for each individual. This curve reflected the extent of deviation from normative gait patterns and the MDP_{mean} is the average of the 51 MDP values calculated during a gait cycle.

Statistical analysis

We summarised continuous variables using distribution-appropriate measures: mean with 95% confidence intervals for approximately symmetric variables; observed ranges were reported for clinical context. To estimate the association between pain intensity and the mean MDP score, we fit ordinary least squares (OLS) linear regressions. The adjusted model included a natural cubic spline for Year (df = 4) to flexibly account for nonlinear temporal trends, with heteroskedasticity-consistent standard errors (HC3). The spline basis terms were included as individual predictors in the model output. For interpretability, we also report an unadjusted model with pain intensity as the sole predictor. Model assumptions (linearity, homoscedasticity,

and normality of residuals) were evaluated using residuals-versus-fitted, Q–Q, and scale–location plots. Sensitivity analyses included modelling Year as a categorical fixed effect and refitting models using conventional (non-robust) standard errors. We report regression coefficients, 95% confidence intervals, p-values, R-squared, and adjusted R-squared, using a two-sided alpha of 0.05. All analyses were conducted in Python (pandas, patsy, statsmodels).

Results

No significant differences were observed between groups in anthropometric or descriptive characteristics, nor in the distribution of reported pain levels. Table 1 summarises the mean and 95% confidence intervals for each variable. The average MDP score was 13.17° (95% CI: 12.73°–13.61°), reflecting the mean extent of deviation from typical gait patterns. MDP waveform profiles are presented in Figure 1.

Pain intensity, assessed via a 0–10 VAS, was predominantly moderate to high, with most responses ranging from 5 to 8, indicating a substantial pain burden in the sample.

Using ordinary least squares regression, we then examined the relationship between pain intensity and mean MDP score. In the unadjusted model, higher pain intensity was strongly associated with greater movement deviation ($\beta = 1.99$; 95% CI: 1.93–2.04; $p < 0.001$; $R^2 = 0.920$; see Table 2). This positive association is visually evident in the correlation figure, where OLS, robust, and year-adjusted fits closely align (Figure 2).

In the adjusted model, which incorporated a natural cubic spline for Year (df = 4) to flexibly account for nonlinear temporal effects and used heteroskedasticity-consistent (HC3) standard errors, the association remained nearly unchanged ($\beta = 1.98$; 95% CI: 1.93–2.04; $p < 0.001$; $R^2 = 0.921$; see Table 3). Diagnostics and temporal effects are shown in the composite figure, indicating acceptable residual behaviour and only modest temporal variation (Figure3).

Model fit statistics are reported in Table 4 and indicate excellent explanatory power. With a final analytic sample of n = 571, statistical power was high. The minimally detectable slope at 90% power and $\alpha = 0.05$ was approximately 0.08, well below the observed slope (~1.98–1.99), indicating precise and robust estimation.

Discussion

This study identified a very strong relationship between pain intensity and a multidimensional gait deviation index, MDP, with each 1-point increase on the VAS predicting

approximately 2° greater overall gait deviation, and the model explaining 92% of the variance. This pattern remained consistent after adjusting for differences across years of data collection, indicating a stable relationship. Prior literature relating pain to single, or a few discrete biomechanical variables generally reports much weaker or inconsistent associations, for example, vertical ground reaction force peaks and loading rate correlated moderately with pain and explained a minority of variance in pain [29], and knee abductor moment impulse showed only moderate correlations with pain and PFJ stress [30]. Experimental provocation and task studies have reported stronger within task pain biomechanics links (e.g., increased pain after loading associated with increased loading rates or dynamic knee valgus), but in much smaller samples and non-walking tasks [16,17]. These comparisons indicate that the present finding is uniquely significant in magnitude and precision relative to typical single-variable studies.

The observed relationship between gait deviation and pain intensity can be explained by the interaction of peripheral and central mechanisms that alter movement control in the presence of pain. Studies provide complementary evidence for this phenomenon. For instance, increased pain levels lead to greater frontal-plane movement and changed neuromuscular activation patterns [17]. Research has found that women with PFP exhibit lower motor complexity and altered muscle synergies during walking, indicating a reorganisation of neural control [31]. Additionally, electromyography studies reveal changes in quadriceps and hamstring activation, as well as alterations in knee flexion angles during PFP gait [32].

Subjects often employ neuromechanical strategies that aim to reduce the load on the PFJ, resulting in decreased patellofemoral joint reaction forces [33]. Furthermore, there are links between peripheral load and response, such as higher loading rates being associated with increased pain [16] which support the idea that pain drives changes in gait mechanics.

Collectively, these findings point to plausible mechanisms, including protective unloading that reduces the load on the PFJ and alters step and stride patterns to minimise painful joint stress [33]. There are also changes in motor control, characterised by a redistribution of muscle activation and reduced complexity, which affects joint movements throughout the gait cycle [31,32]. Neuromuscular adaptations, such as increased co-contraction or timing shifts, modify joint moments and kinematics in response to pain [32]. Lastly, sensory modulation and sensitisation, where widespread or localised hyperalgesia alters motor output, can lead to persistent changes in movement even after the load has been applied [34].

The MDP is an AI-based, multidimensional summary that measures Euclidean deviation across 13 kinematic curves, including the hip, knee, ankle, foot, pelvis, and trunk. This study uses a SOM, providing a single continuous measure of overall deviation from typical gait. In a

broader perspective, the MDP has been applied across multiple functional tasks, including gait, to compare women with and without patellofemoral pain. In that study, kinematic variables were categorized within a clinically oriented framework encompassing proximal, local, distal factors, and malalignment. The analysis showed that the MDP is sensitive to clinically meaningful differences and has a strong capacity to distinguish between groups. Taken together, the evidence supports the use of the MDP as a comprehensive summary measure that effectively captures coordinated and distributed deviations throughout the gait cycle and may be more clinically applicable in patellofemoral pain than traditional metrics such as discrete joint peaks or spatiotemporal parameters [35].

Previous research relying on discrete single-plane or single-task metrics captures only parts of the gait signal, often resulting in weaker links to pain [16,29,33]. Unlike discrete joint or metric variables, which usually involve 1 to 3 variables or peak values [16,30] and spatiotemporal metrics assessing overall walking parameters such as speed, step length, and stance percentage [36] the MDP offers a multi-segment, waveform-level summary. Discrete variables might miss distributed changes and timing shifts [16,30], while spatiotemporal measures tend to detect general changes [36], but do not address joint specific waveform abnormalities. In our large sample, the MDP showed a very strong link with pain, whereas discrete metrics often had only moderate or inconsistent connections [16,29,30]. Although spatiotemporal measures have been linked to severity in specific groups, they explain less variance [36].

When considering the clinical implications, it is crucial to recognise that three-dimensional gait analysis remains the gold standard for assessing human movement. The MDP adds value because it utilises the complete kinematic time-series data across the entire gait cycle, rather than relying on single, categorical endpoints. We see the MDP as a powerful quantitative tool for contextualising symptom burden and monitoring changes over time. It is particularly valuable in clinical gait analysis laboratories, research settings, and well-resourced healthcare services, and can be gradually translated into routine care.

However, this translation will likely require accessible tools that produce reliable, time-normalised waveforms. Examples include validated and reliable 2D kinematic systems or other low-cost instruments, which would allow for MDP computation outside of 3D laboratories. It is important to approach the lack of access to 3D assessments with caution. Using simplified, lower-cost methods without proper validation could compromise the accurate interpretation of gait abnormalities, leading to incorrect diagnostic or therapeutic decisions. Future research should focus on rigorously validating these pragmatic methods against 3D benchmarks and

defining acceptable limits of agreement. Until such validation is achieved, outputs from simplified systems should be used conservatively, primarily for benchmarking and to guide targeted joint-level assessments, rather than as the sole basis for clinical decision making.

Clinically, the MDP delivers a single continuous score suitable for long-term monitoring. However, a minimal clinically important difference (MCID) has yet to be established. Overall, the MDP can improve sensitivity to pain-related gait changes, enable single-metric monitoring of overall kinematic variations and enhance statistical power in trials. Still, clinicians and researchers should focus on developing the MCID and conducting external validation in different samples before the MDP is broadly adopted in clinical practice.

This study has several limitations that should be recognised. As with any retrospective design, the potential for selection bias cannot be eliminated. However, this risk was reduced by using standardised inclusion criteria and consistent data collection procedures. The study relies on self-reported pain measures using the VAS, which, although commonly employed, can be subjective and vary between individuals. Additionally, the sample comprises physically active young females from a single geographic area, which may restrict the generalisability of the findings to other populations or age groups. Finally, although the MDP offers a comprehensive analysis of gait deviations, it does not consider other factors such as muscle strength, endurance, or psychological aspects that may also influence gait patterns and pain perception.

Conclusion

This comprehensive study reveals a clear and clinically significant dose–response relationship between pain intensity and a global gait deviation index, as determined by AI. These findings highlight the potential of multidimensional gait summaries, while also underlining the need for prospective validation, the development of the MCID, and targeted intervention studies to establish causality and improve clinical use.

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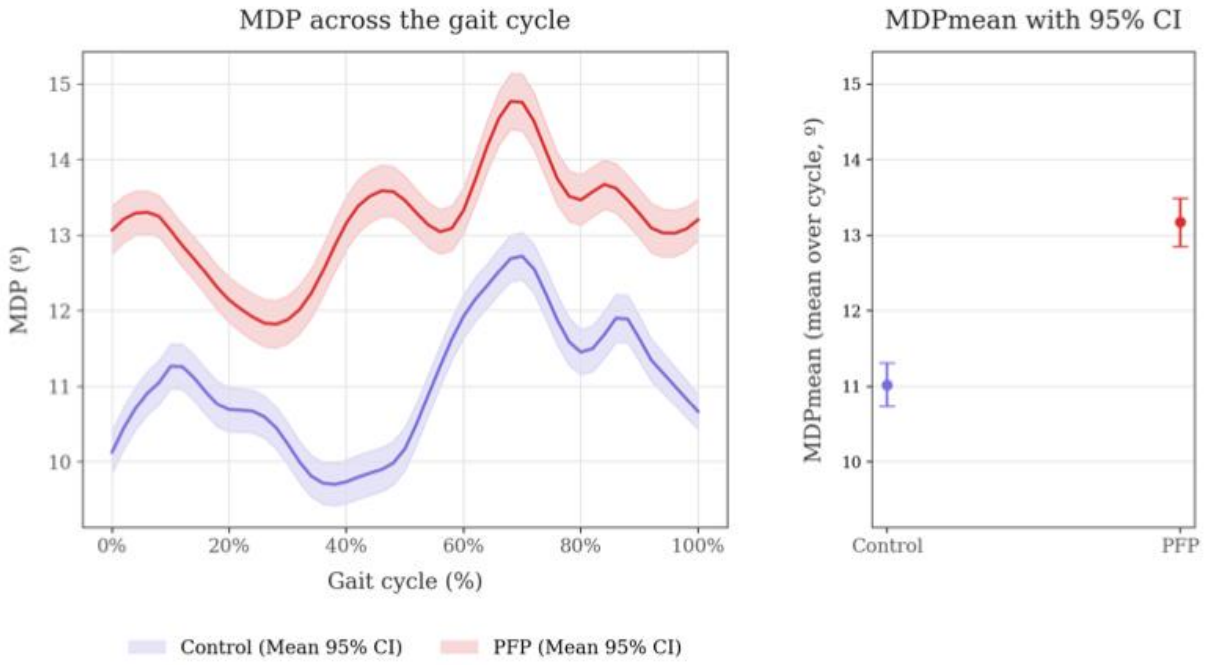

Figure 1. Movement deviation profile (mean and 95% confidence interval) for gait in the control group (blue) and PFP group (red).

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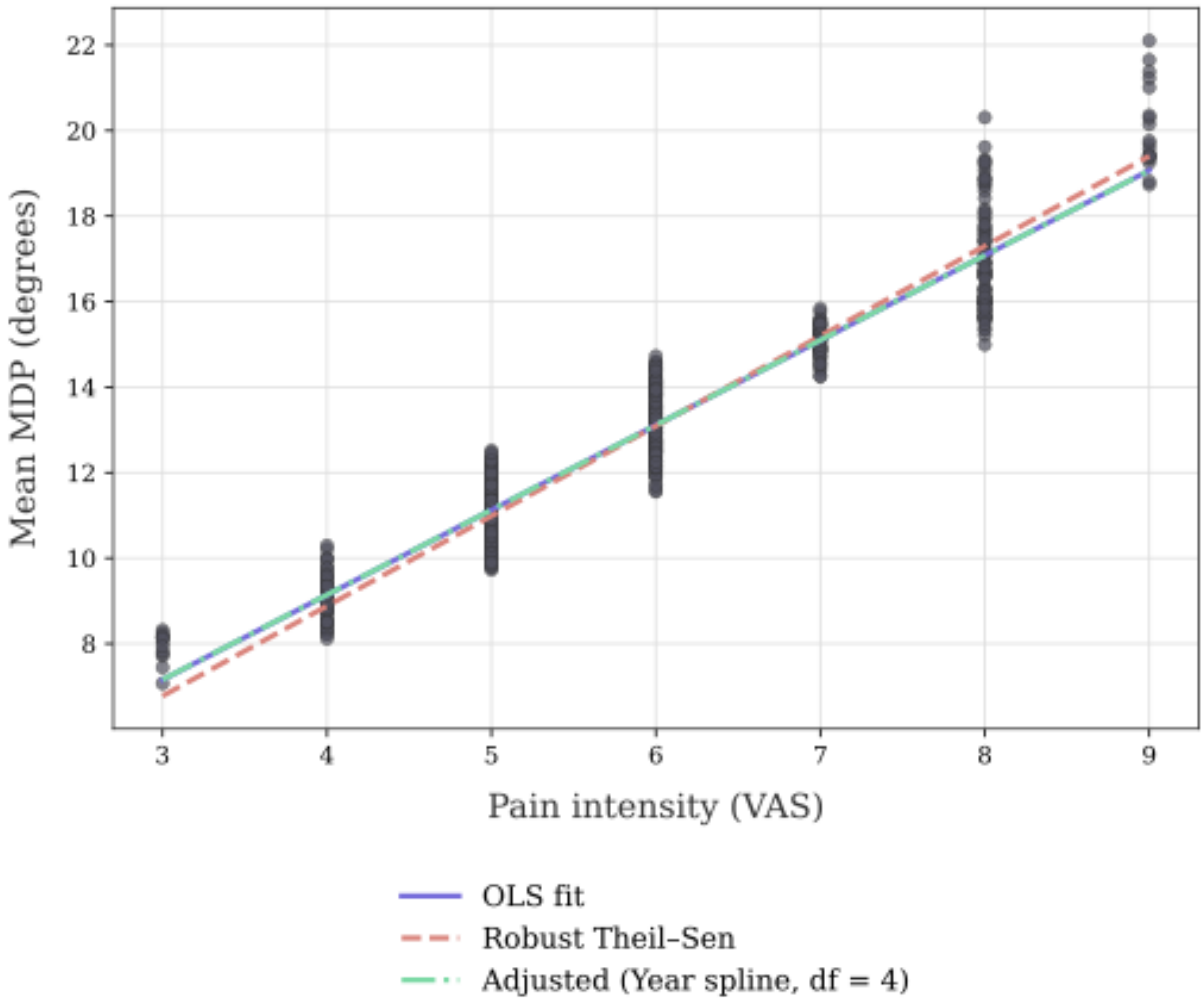

Figure 2. Correlation between pain intensity (VAS) and mean MDP. Points represent individual observations. The solid line shows the OLS fit with a bootstrap 95% confidence ribbon; the dashed line is a robust Theil–Sen estimate; the dash–dot line is the model adjusted for year via a cubic spline. The close agreement among lines indicates a consistent positive association not driven by outliers or temporal trends.

Figure 3

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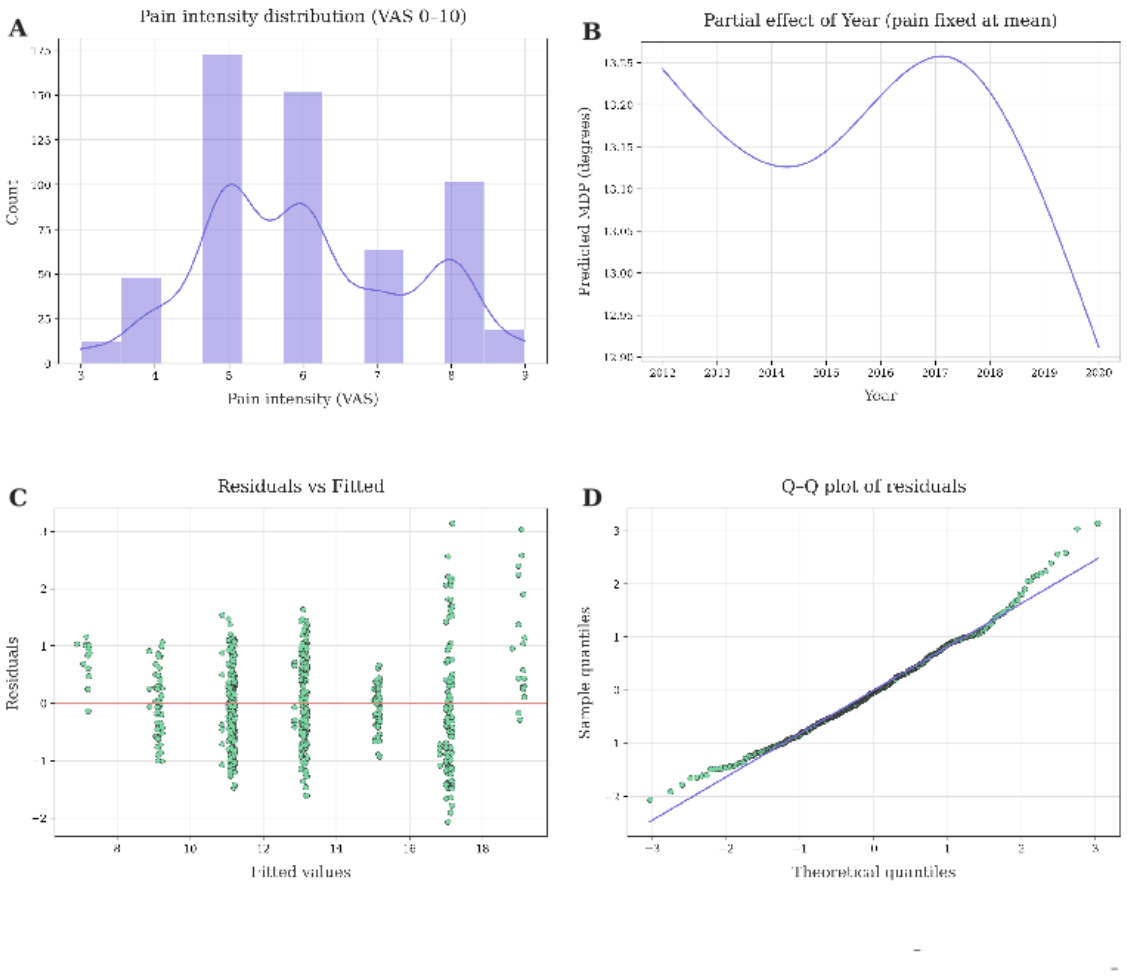

Figure 3. Temporal effect and diagnostics for the adjusted MDP model. A: Pain intensity distribution (VAS 0 10). B: Partial effect of Year (natural cubic spline, df = 4) with pain fixed at the sample mean. C: Residuals vs fitted values (HC3 standard errors used in modelling). D: Q-Q plot of residuals indicating approximate normality.

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Table 1. Anthropometric and descriptive characteristics of the sample and distribution of pain levels.

	PFP	**Unimpaired**
Age (years)	23.98 ± 4.23 (22.8 – 25.16)	23.97 ± 4.75 (21.70 – 26.24)
Height (m)	1.63 ± 0.30 (1.60 – 1.65)	1.62 ± (1.61 – 1.63)
Body mass (kg)	57.61 ± 5.13 (54.7 – 60.52)	57.65 ± 5.04 (55.07 – 60.23)
VAS (0-10 points)	6.03 ± 1.45 (5.91 – 6.15)	-
Normalized speed (m/s)	1.12 ± 0.13 (1.11 – 1.13)	1.13 ± 0.11 (1.12 – 1.14)
VAS	**N**	**%**
3 (0-10 points)	13	2.51
4 (0-10 points)	48	9.28
5 (0-10 points)	173	33.46
6 (0-10 points)	152	29.40
7 (0-10 points)	64	12.38
8 (0-10 points)	102	19.73
9 (0-10 points)	19	3.68

Mean and 95% confidence interval in brackets; VAS: visual analog scale; normalized speed = speed / sqrt (body height/average body height).

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Table 2. Primary linear regression model of MDP on pain intensity (adjusted for year)

Term	Estimate	95% CI	SE	p-value
Intercept (constant)	0.930	(0.660–1.210)	0.140	<0.001
Pain intensity (0–10 VAS)	1.980	(1.930–2.040)	0.030	<0.001
cr(Year, df=4)[0]	0.340	(0.170–0.510)	0.090	<0.001
cr(Year, df=4)[1]	0.230	(0.100–0.360)	0.070	<0.001
cr(Year, df=4)[2]	0.350	(0.200–0.510)	0.080	<0.001
cr(Year, df=4)[3]	0.010	(–0.210–0.240)	0.110	0.925

Primary model includes pain intensity and a natural cubic spline term for year (4 degrees of freedom). Robust standard errors (HC3) were used. The spline basis terms are denoted cr(Year, df=4)[k], representing the k-th basis function for year.

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Table 3: Adjusted linear regression model of MDP and pain intensity over the years

Term	Estimate	95% CI	SE	p-value
Intercept (constant)	0.930	(0.660–1.210)	0.140	<0.001
Pain intensity (0–10 VAS)	1.980	(1.930–2.040)	0.030	<0.001
cr(Year, df=4)[0]	0.340	(0.170–0.510)	0.090	<0.001
cr(Year, df=4)[1]	0.230	(0.100–0.360)	0.070	<0.001
cr(Year, df=4)[2]	0.350	(0.200–0.510)	0.080	<0.001
cr(Year, df=4)[3]	0.010	(–0.210–0.240)	0.110	0.925

Adjusted model includes pain intensity and a natural cubic spline term for year (4 degrees of freedom). Robust standard errors (HC3) were used. The spline basis terms are denoted cr(Year, df=4)[k], representing the k-th basis function for year.

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Table 4. Model fit indices for regression models

Model	N	R^2	Adj. R^2	AIC	BIC
Unadjusted	571	0.920	0.920	1400.067	1408.762
Adjusted	571	0.921	0.920	1401.266	1423.003

Adjusted model fit statistics for the unadjusted and primary regression models. N = sample size; R^2 = R-squared; Adj. R^2 = adjusted R-squared; AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion.

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