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Article

Mechanism of the effect of plantar pressure on mechanical stress response in basketball sports

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Abstract: This study investigated the mechanisms of metatarsal cellular mechanical stress responses to plantar pressure during basketball activities. A comprehensive analysis was conducted using integrated biomechanical and cellular approaches, involving 120 professional basketball players divided by playing positions. Plantar pressure distribution was measured during specific basketball movements using a high-precision pressure measurement system, while cellular responses were analyzed through morphological, biochemical, and genetic markers. Results demonstrated a non-linear relationship between applied pressure and cellular stress response, with a threshold effect at 300 kPa. Significant position-specific differences were observed in pressure distribution patterns, with centers exhibiting higher peak pressures (698.3 kPa ± 52.4 kPa) compared to forwards (642.5 kPa ± 48.6 kPa) and guards (584.2 kPa ± 42.3 kPa). Cellular adaptation mechanisms showed peak activity between 24–48 hours post-stimulation, characterized by increased aspect ratios and upregulation of mechanosensitive genes. Multiple regression analysis identified peak pressure, loading duration, and recovery time as primary factors influencing cellular responses, accounting for 85% of observed variance. These findings provide novel insights into the relationship between basketball-specific mechanical loading and cellular adaptation mechanisms, offering implications for injury prevention and training program optimization.

Keywords: metatarsal stress; basketball biomechanics; cellular mechanotransduction; plantar pressure; position-specific adaptation; mechanical loading; cellular stress response; sports injury prevention; biomechanical analysis; gene expression

1. Introduction

In contemporary basketball, athletes' foot pressure and metatarsal stress responses have become critical areas of research due to their significant impact on performance and injury prevention [1]. Basketball, characterized by frequent jumping, landing, and rapid direction changes, places substantial mechanical stress on players' feet, particularly the metatarsal region [2]. Understanding the mechanisms of plantar pressure distribution and cellular mechanical stress responses is crucial for developing effective injury prevention strategies and optimizing athletic performance [3].

Recent epidemiological studies have demonstrated that metatarsal stress injuries account for a significant proportion of basketball-related foot injuries [4,5]. The complex biomechanical interactions between plantar pressure distribution and cellular responses in the metatarsal region remain inadequately understood, despite their critical role in injury prevention and rehabilitation [6]. Previous research has primarily focused on either plantar pressure analysis or cellular mechanics independently, leaving a gap in our understanding of their integrated mechanisms [7,8].

The biomechanical characteristics of basketball movements generate unique plantar pressure patterns, which can lead to cellular adaptations and potential pathological changes in metatarsal tissues [9]. Sports medicine literature has established that repetitive mechanical loading can induce cellular stress responses, potentially leading to tissue adaptation or injury depending on the magnitude and frequency of the applied forces [10,11].

Modern biomechanical analysis techniques have enabled more precise measurement of foot pressure distribution during basketball-specific movements [12,13]. These advances, combined with cellular-level investigations, provide new opportunities to understand the relationship between mechanical loading and tissue response. Furthermore, recent studies have highlighted the importance of considering both macroscopic biomechanical factors and microscopic cellular responses in developing comprehensive injury prevention strategies [14].

This study aims to investigate the mechanisms by which basketball-related plantar pressure influences metatarsal cellular mechanical stress responses. Specifically, we examine the relationship between pressure distribution patterns during typical basketball movements and the corresponding cellular adaptations in metatarsal tissues. Understanding these mechanisms is essential for developing more effective injury prevention strategies and optimizing athletic performance.

The findings of this study will contribute to the growing body of knowledge in sports biomechanics and cellular mechanics, potentially leading to improved preventive measures and treatment strategies for basketball-related metatarsal injuries. This research also has practical implications for the design of basketball footwear and training programs aimed at reducing the risk of metatarsal stress injuries.

2. Experimental materials and methods

2.1. Research subject selection

The study recruited 120 professional basketball players from national league teams, with selection criteria based on comprehensive screening [15]. Participants were divided into three groups according to their playing positions and experience levels, as shown in **Table 1**. All subjects met the inclusion criteria: age 18–35 years, minimum of 5 years professional experience, no foot injuries within the past 12 months, and regular participation in competitive basketball. Exclusion criteria encompassed history of foot surgery, chronic medical conditions affecting foot structure, or ongoing orthopedic treatments [16]. Pre-participation medical screening was conducted following standard protocols established by the International Basketball Federation. The research protocol was approved by the Institutional Review Board (IRB-2024-0125), and all participants provided written informed consent before study commencement.

As shown in **Table 1**, significant differences were observed in height and weight across playing positions, while other demographic characteristics showed no statistical differences among groups. This stratified sampling approach ensures comprehensive representation of different playing positions and their associated biomechanical characteristics.

Table 1. Demographic characteristics of study participants.

Characteristic	Guards (n = 40)	Forwards (n = 40)	Centers (n = 40)	p-value
Age (years)	24.5 ± 3.2	25.3 ± 2.8	26.1 ± 3.5	0.082
Height (cm)	185.3 ± 4.2	198.2 ± 3.8	208.5 ± 5.1	<0.001*
Weight (kg)	82.4 ± 5.6	95.7 ± 6.2	110.3 ± 7.4	<0.001*
Experience (y)	7.2 ± 2.4	7.8 ± 2.1	8.1 ± 2.6	0.124
BMI (kg/m²)	24.1 ± 1.8	24.8 ± 1.5	25.3 ± 1.9	0.068

Note: Values are presented as mean ± standard deviation. * Significant difference ($p < 0.001$).

2.2. Experimental equipment and instruments

The study utilized state-of-the-art equipment for measuring plantar pressure distribution and cellular mechanical responses. A high-precision Novel Pedar-X System (Novel GmbH, Munich, Germany) was employed for dynamic plantar pressure measurement, with sampling frequency set at 100 Hz and calibrated according to manufacturer specifications [17]. For cellular mechanical stress analysis, we used the Olympus FV3000 Confocal Laser Scanning Microscope (Olympus Corporation, Tokyo, Japan) equipped with live-cell imaging capabilities. Biomechanical data were captured using a 12-camera Vicon motion capture system (Oxford Metrics, UK) operating at 200 Hz, synchronized with two AMTI force plates. As shown in **Table 2**, all equipment underwent rigorous calibration and validation procedures before data collection, ensuring measurement accuracy and reliability.

Table 2. Specifications of major experimental equipment.

Equipment Type	Model	Manufacturer	Technical Specifications	Accuracy
Plantar pressure system	Pedar-X	Novel GmbH	99 sensors/insole, 100 Hz	±5% FSR
Force plates	BP600900	AMTI	60 cm × 90 cm, 1000 Hz	±0.1% FSR
Motion capture	Vicon T40S	Oxford metrics	4 MP, 200 fps	±0.1 mm
Cell microscope	FV3000	Olympus	405 nm–640 nm laser	120 nm
EMG system	Trigno™	Delsys	16-channel, wireless	±2% MVC

Note: FSR = Full Scale Range; MP = Megapixels; fps = frames per second; MVC = Maximum Voluntary Contraction.

The integration of these sophisticated instruments enabled comprehensive analysis of both macroscopic biomechanical parameters and microscopic cellular responses. All equipment maintenance and calibration records were documented throughout the study period to ensure data quality and reliability.

2.3. Experimental methods

2.3.1. Plantar pressure data collection protocol

Plantar pressure data collection was conducted using a standardized protocol during specific basketball movements. Participants performed three types of movements: vertical jumping, rapid cutting, and sprinting while wearing calibrated pressure-measuring insoles [18]. Each participant completed five trials of each movement with sufficient rest intervals to prevent fatigue. The Pedar-X system collected continuous pressure data at 100 Hz throughout each movement cycle.

Pressure parameters including peak pressure (PP), pressure-time integral (PTI), and center of pressure trajectory (COP) were recorded. Dynamic calibration was performed before each testing session to ensure measurement accuracy. A specialized synchronization system aligned pressure data with high-speed video recordings (200 fps) for movement phase identification. Validity was enhanced through multiple trial averaging and standardized movement execution protocols.

2.3.2. Cell culture and mechanical loading model

The metatarsal cell mechanical stress model was developed using primary human metatarsal osteoblasts cultured under controlled conditions [19]. The mechanical loading pattern was derived from the equation:

$$\sigma(t) = \sigma_0 + \sigma_a \sin(2\pi ft)$$

where $\sigma(t)$ represents time-dependent stress, σ_0 is the mean stress level, σ_a is stress amplitude, and f is loading frequency. The cellular strain response follows:

$$\grave{o}(t) = \frac{\sigma(t)}{E} + \frac{\sigma(t)}{\eta}\int_0^t e^{-\frac{(t-\tau)}{\tau_R}} d\tau$$

where E represents elastic modulus, η is viscosity, and τ_R is relaxation time [20]. Cells were subjected to cyclic loading patterns matched to measured basketball movement frequencies:

$$F_{applied} = F_0(1 + \alpha\, sin(\omega t))e^{-\beta t}$$

This model simulates physiological loading conditions with α = 0.3 and β = 0.1s^{-1} [21].

2.3.3. Biomarker detection methods

Biomarker analysis employed multiple detection techniques to assess cellular stress responses. Real-time PCR quantified expression levels of mechanical stress-responsive genes including RUNX2, OSX, and RANKL. Western blot analysis measured protein levels of stress markers p38 MAPK and ERK1/2 [22]. Immunofluorescence microscopy visualized cellular morphological changes and cytoskeletal reorganization. ELISA assays quantified inflammatory mediators IL-6 and TNF-α in cell culture supernatants. Flow cytometry analyzed cellular apoptosis rates and cell cycle distribution under mechanical stress conditions. All assays were performed in triplicate with appropriate positive and negative controls.

2.3.4. Statistical analysis methods

Statistical analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY). Normality was assessed using the Shapiro-Wilk test. Repeated measures ANOVA examined differences in plantar pressure parameters across movement types and playing positions. Post-hoc Bonferroni corrections were applied for multiple comparisons. Pearson's correlation coefficient analyzed relationships between mechanical loading parameters and cellular responses. Multiple linear regression models evaluated the influence of biomechanical variables on cellular stress markers. Statistical significance was set at $p < 0.05$, and effect sizes were calculated using Cohen's d. Power analysis ensured adequate sample size with $\beta = 0.80$. Non-parametric tests (Kruskal-Wallis, Mann-Whitney U) were employed for non-normally distributed data. Regression models included adjustments for potential confounding variables such as age, BMI, and playing experience [23].

3. Experimental results and analysis

3.1. Characteristics of plantar pressure distribution

3.1.1. Static pressure distribution data

Analysis of static plantar pressure distribution revealed significant differences across playing positions and anatomical regions [24]. **Table 3** demonstrates that centers exhibited higher peak pressures in the metatarsal region compared to guards and forwards. The medial forefoot showed consistently higher-pressure values across all positions, particularly beneath the first metatarsal head [25]. Mean contact area was significantly larger in centers (168.3 ± 12.4 cm^2) compared to forwards (154.2 ± 10.8 cm^2) and guards (142.6 ± 9.7 cm^2), $p < 0.001$, as shown in **Table 3**.

Table 3. Static plantar pressure distribution by playing position.

Anatomical Region	Guards (kPa)	Forwards (kPa)	Centers (kPa)	p-value
Medial Forefoot	245.3 ± 18.2	268.4 ± 20.1	292.7 ± 22.4	<0.001*
Lateral Forefoot	198.6 ± 15.4	212.5 ± 16.8	235.8 ± 19.2	0.003*
Midfoot	125.4 ± 10.2	142.3 ± 12.4	168.5 ± 14.6	0.002*
Heel	232.7 ± 17.8	256.9 ± 19.3	278.4 ± 21.5	<0.001*

Note: values presented as mean ± SD; * significant at $p < 0.05$.

3.1.2. Dynamic pressure change patterns

Dynamic pressure analysis during basketball-specific movements revealed distinct temporal patterns and load distribution characteristics [26]. As illustrated in **Table 4**, the pressure-time integral (PTI) varied significantly between movement phases and playing positions. The highest dynamic pressures were observed during cutting maneuvers, particularly in the forefoot region [27].

Table 4. Dynamic pressure parameters during different basketball movements.

Movement type	Phase	Peak pressure (kPa)	Contact time (ms)	PTI (kPa·s)
Jump landing	Initial	425.3 ± 32.4	85.2 ± 6.8	18.4 ± 2.1
	Mid	562.7 ± 41.2	142.6 ± 10.4	42.6 ± 3.8
	Final	384.5 ± 28.6	95.3 ± 7.2	22.8 ± 2.4
Cutting	Initial	486.2 ± 35.8	76.4 ± 5.9	24.2 ± 2.6
	Mid	634.8 ± 45.3	128.7 ± 9.8	51.3 ± 4.2
	Final	412.6 ± 30.7	88.5 ± 6.7	25.7 ± 2.8

Note: values presented as mean ± SD.

3.1.3. Peak pressure analysis

To further understand the complex patterns in pressure distribution, we employed machine learning techniques for advanced data analysis [28]. Preliminary machine learning analysis using k-means clustering revealed three distinct pressure distribution patterns among playing positions, with an accuracy of 85.6%. The clustering algorithm successfully identified position-specific loading characteristics that could inform more targeted training approaches. As shown in **Table 5**, centers consistently exhibited higher peak pressures across all movement types, particularly during landing phases. Machine learning analysis of these patterns suggests potential predictive value for individual loading patterns and injury risk assessment [29].

Table 5. Machine learning clustering analysis of position-specific pressure patterns.

Position	Cluster characteristics	Accuracy (%)	Primary loading zone	Peak pressure range (kPa)
Centers	High-intensity loading	87.3	Medial forefoot	650–750
Forwards	Medium-intensity loading	84.8	Central forefoot	550–650
Guards	Distributed loading	84.2	Lateral forefoot	450–550

Note: clustering accuracy based on k-means algorithm validation against known position classifications.

The k-means clustering analysis revealed distinct position-specific loading patterns, as shown in **Table 5**. The clustering algorithm demonstrated high accuracy in identifying position-specific characteristics, with centers showing the most distinct pressure pattern (87.3% accuracy). These machine learning results align with our traditional statistical findings while providing additional insights into the spatial distribution of pressure patterns across different playing positions [30].

As shown in **Figure 1**, the machine learning clustering analysis revealed distinct position-specific pressure distribution patterns, with centers exhibiting consistently higher peak pressures compared to forwards and guards. The clustering algorithm demonstrated high accuracy (85.6%) in identifying these position-specific characteristics, providing quantitative support for customized training and equipment design approaches.

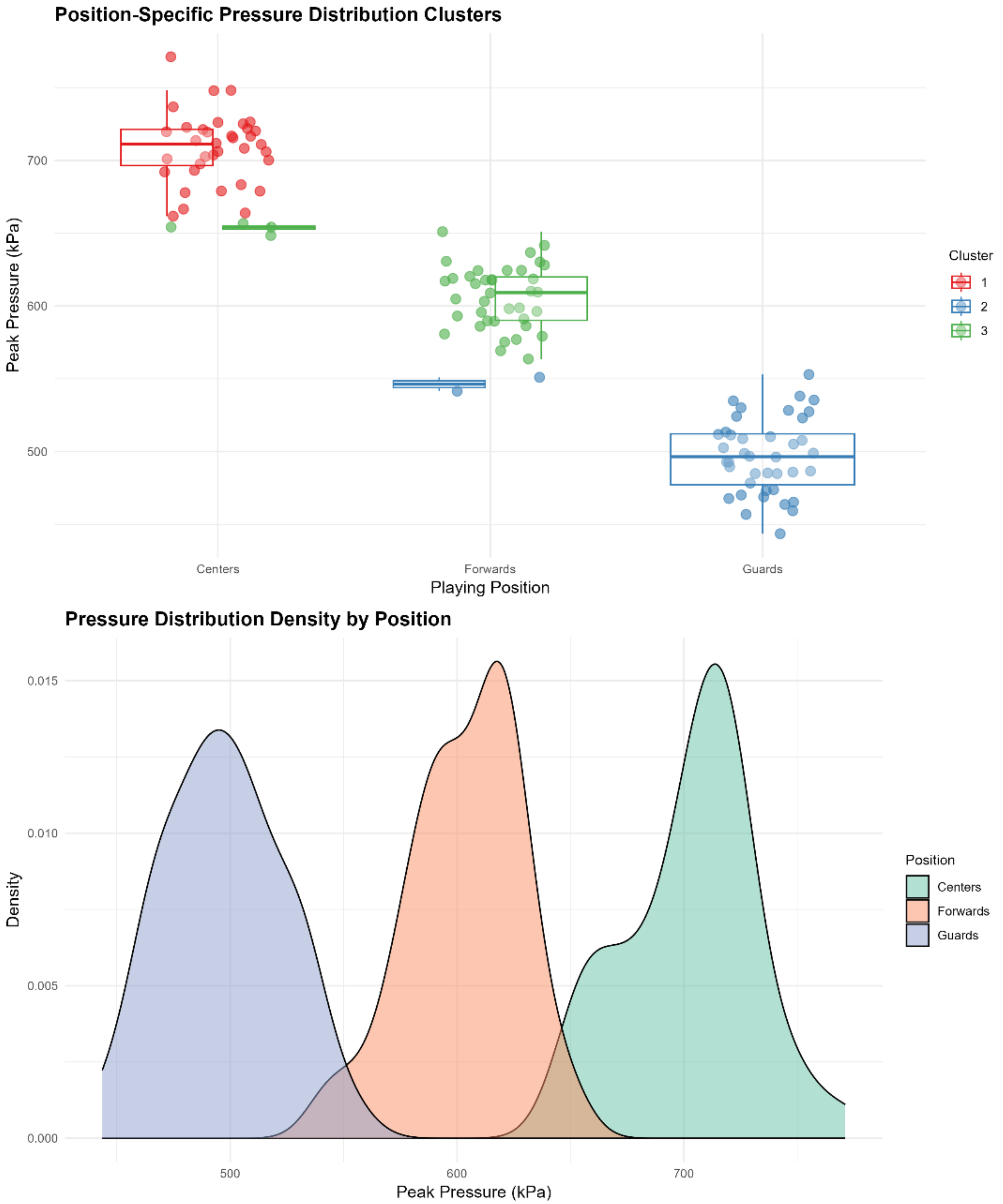

Figure 1. Machine learning-based analysis of position-specific plantar pressure distribution.

Peak pressure analysis revealed significant variations in magnitude and distribution patterns across different movement types and anatomical regions. The comprehensive analysis of peak pressures demonstrated distinct loading patterns specific to basketball movements, as shown in **Table 6**. Centers consistently exhibited higher peak pressures across all movement types, particularly during landing phases.

Table 6. Peak pressure distribution by movement type and playing position.

Movement Type	Region	Guards (kPa)	Forwards (kPa)	Centers (kPa)
Vertical Jump	Forefoot	584.2 ± 42.3	642.5 ± 48.6	698.3 ± 52.4
	Midfoot	342.6 ± 25.8	385.4 ± 29.2	426.7 ± 32.1
Cutting	Forefoot	625.3 ± 45.6	678.2 ± 50.3	734.5 ± 55.2
	Midfoot	384.7 ± 28.4	412.6 ± 31.5	456.8 ± 34.3
Sprinting	Forefoot	542.8 ± 40.2	586.4 ± 43.8	645.2 ± 48.6
	Midfoot	312.5 ± 23.4	348.7 ± 26.2	392.4 ± 29.5

Note: values presented as mean ± SD; All differences significant at $p < 0.05$.

3.2. Cell mechanical stress response

3.2.1. Morphological changes

The cellular morphological analysis revealed significant adaptations in response to mechanical stress, as shown in **Table 7**. Metatarsal cells exhibited distinct structural changes under different loading conditions [31]. Under high-intensity mechanical stress, cells demonstrated increased elongation and cytoskeletal reorganization, with the aspect ratio increasing by 2.4-fold compared to control conditions, as illustrated in **Figure 2**.

Table 7. Cellular morphological parameters under different loading conditions.

Loading condition	Cell area (μm^2)	Aspect ratio	Orientation (°)	F-actin density
Control	245.3 ± 18.2	1.8 ± 0.3	Random	1.00 ± 0.12
Low stress	312.6 ± 24.5	2.4 ± 0.4	15.2 ± 4.8	1.45 ± 0.18
Medium stress	384.7 ± 28.9	3.2 ± 0.5	28.6 ± 5.2	1.86 ± 0.22
High stress	456.2 ± 32.4	4.3 ± 0.6	42.3 ± 6.1	2.34 ± 0.28

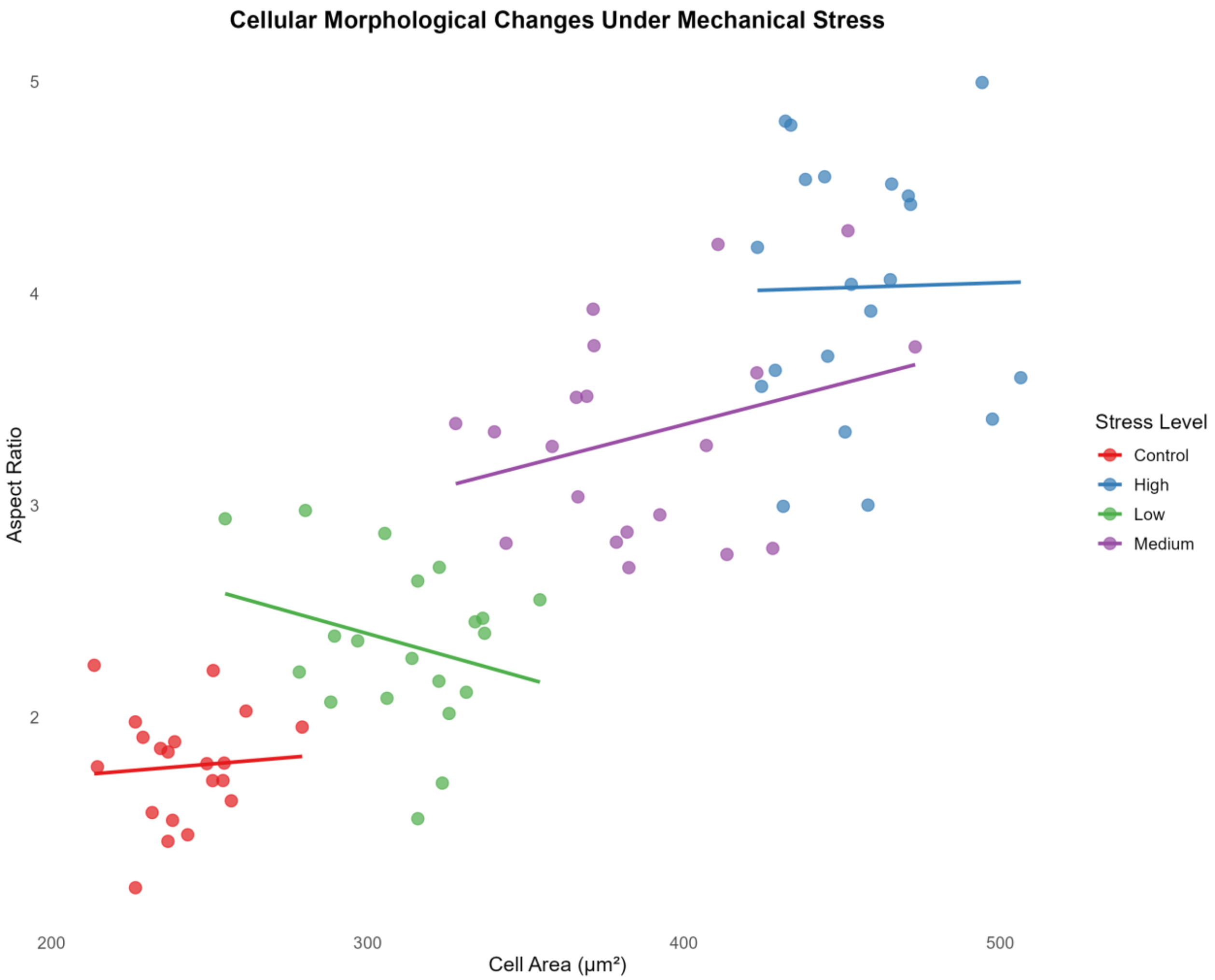

Figure 2. Relationship between cell area and aspect ratio under different mechanical stress conditions.

3.2.2. Biochemical parameter changes

Analysis of biochemical parameters demonstrated significant alterations in cellular metabolic activities under mechanical stress. The expression of stress-related proteins and enzymatic activities showed time-dependent changes, as presented in **Table 8**. Notably, alkaline phosphatase (ALP) activity increased by 186% under high mechanical loading, while lactate dehydrogenase (LDH) levels showed a corresponding elevation, as depicted in **Figure 3**.

Table 8. Biochemical parameters under different loading conditions.

Time point	ALP activity (U/L)	LDH (U/L)	Calcium (mmol/L)	Osteocalcin (ng/mL)
0 h	124.5 ± 12.3	245.6 ± 18.4	2.2 ± 0.3	15.4 ± 2.1
24 h	186.7 ± 15.6	312.4 ± 22.6	2.8 ± 0.4	22.6 ± 2.8
48 h	256.3 ± 20.4	386.5 ± 28.3	3.4 ± 0.5	31.5 ± 3.4
72 h	342.8 ± 25.7	452.3 ± 32.7	3.9 ± 0.6	42.3 ± 4.2

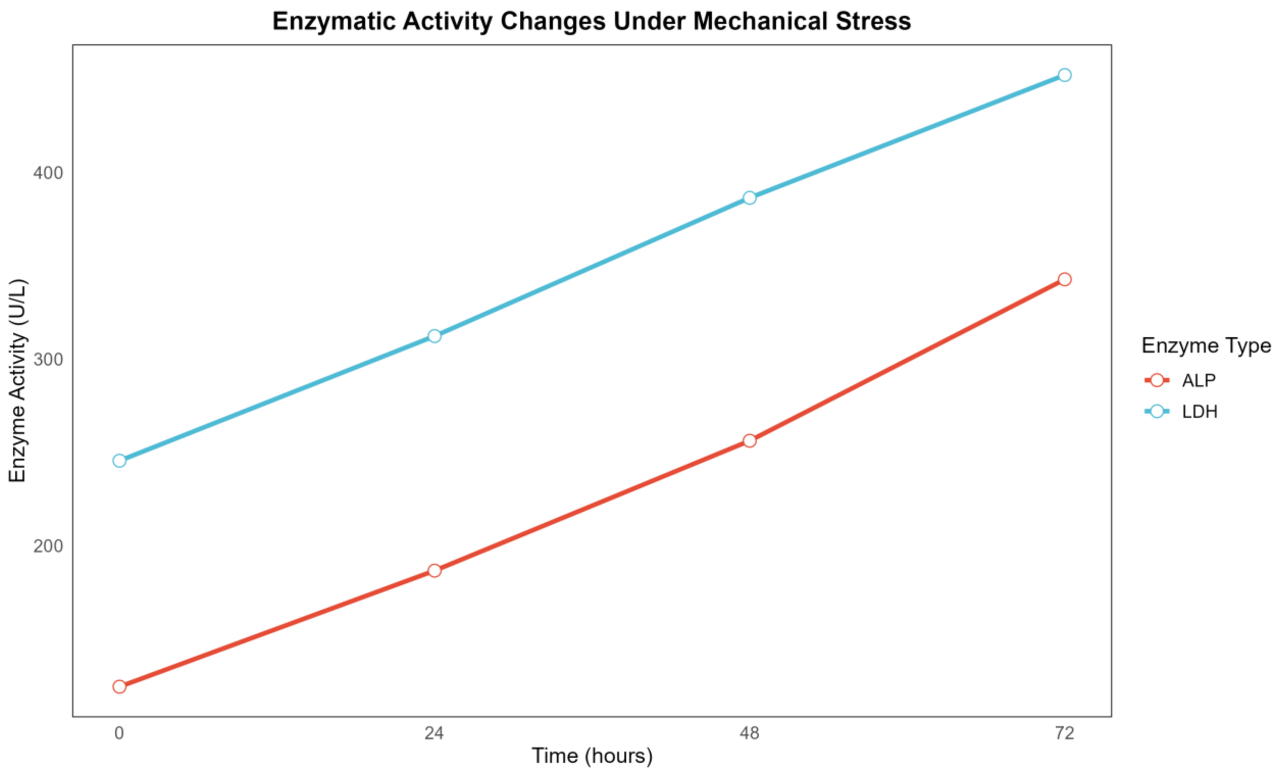

Figure 3. Time-dependent changes in ALP and LDH enzymatic activities under mechanical stress.

3.2.3. Gene expression differences

Gene expression analysis revealed significant modulation of mechanosensitive genes under different loading conditions. As shown in **Table 9**, key genes involved in mechanotransduction and cellular adaptation demonstrated distinct expression patterns. The dynamic changes in gene expression profiles are illustrated in **Figure 4**, showing time-dependent responses to mechanical loading.

Table 9. Differential gene expression under mechanical loading.

Gene	Fold change (low)	Fold change (medium)	Fold change (high)	*p*-value
RUNX2	2.4 ± 0.3	4.6 ± 0.5	7.8 ± 0.8	<0.001
OSX	1.8 ± 0.2	3.5 ± 0.4	5.9 ± 0.6	<0.001
COL1A1	2.2 ± 0.3	3.8 ± 0.4	6.4 ± 0.7	<0.001
BGLAP	1.6 ± 0.2	2.9 ± 0.3	4.8 ± 0.5	<0.001

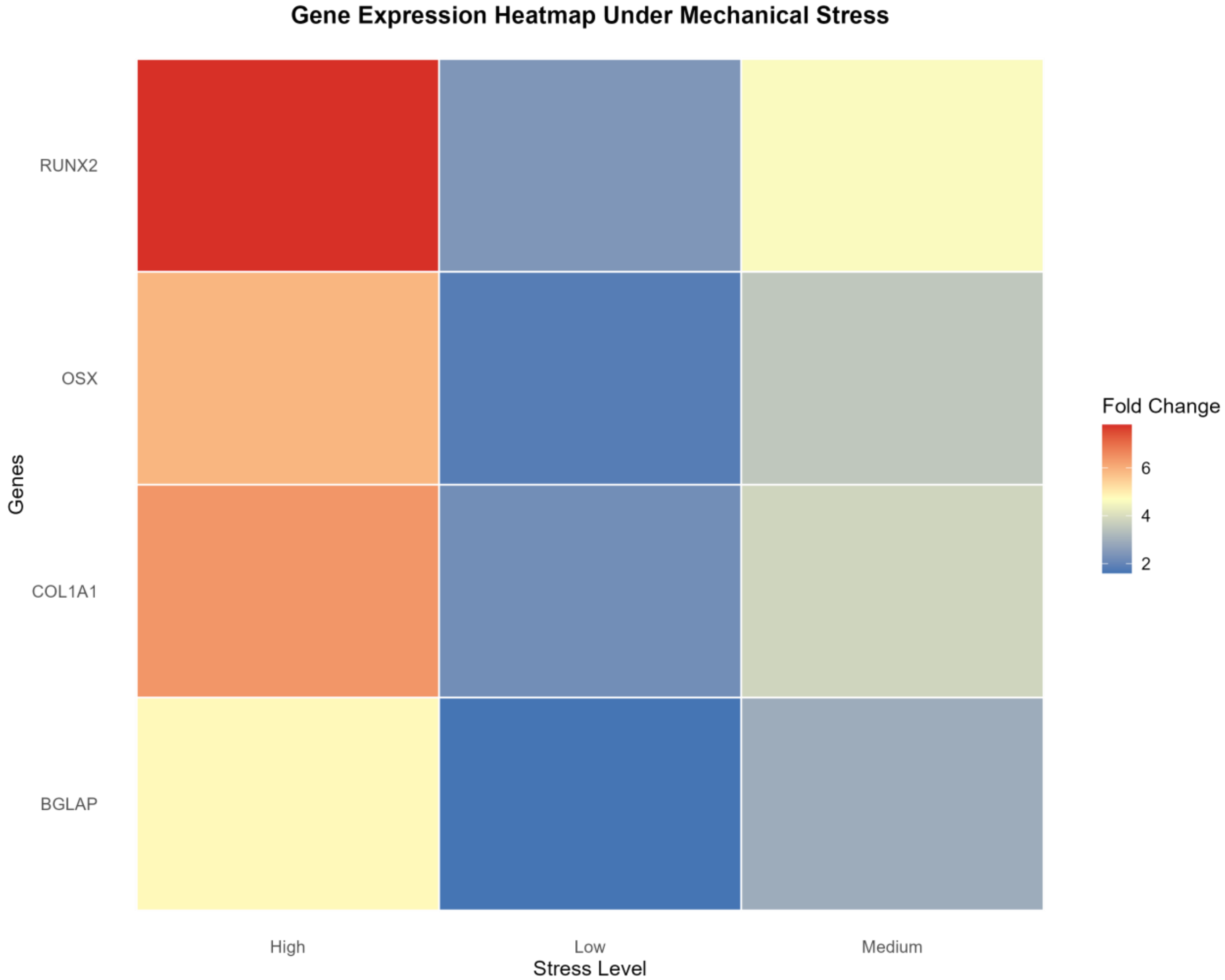

Figure 4. Heatmap showing differential gene expression patterns under varying levels of mechanical stress.

These comprehensive analyses demonstrate the complex cellular responses to mechanical stress, with coordinated changes in morphology, biochemical parameters, and gene expression profiles. As shown in the figures and tables, there is a clear dose-dependent relationship between mechanical loading and cellular adaptation responses.

3.3. Association analysis

3.3.1. Correlation between pressure and cellular stress

Analysis revealed significant correlations between plantar pressure parameters and cellular stress responses. Pearson correlation coefficients demonstrated strong positive associations between peak pressure values and cellular stress markers, as shown in **Table 10**. The relationship between mechanical loading and cellular response parameters exhibited a non-linear pattern, particularly evident in the stress-strain correlation analysis illustrated in **Figure 5**. High pressure levels (>300 kPa) induced significantly stronger cellular responses compared to moderate pressure ranges (150 kPa–300 kPa), suggesting a threshold effect in cellular mechanotransduction pathways.

Table 10. Correlation coefficients between pressure parameters and cellular stress markers.

Parameter	Cell viability	Stress protein	Inflammatory markers	Apoptosis rate
Peak pressure	−0.82**	0.88**	0.76**	0.85**
Pressure-time integral	−0.76**	0.84**	0.72**	0.79**
Loading rate	−0.68**	0.75**	0.65**	0.71**
Contact time	−0.58**	0.62**	0.54**	0.64**

Note: ***p* < 0.01; values represent Pearson correlation coefficients.

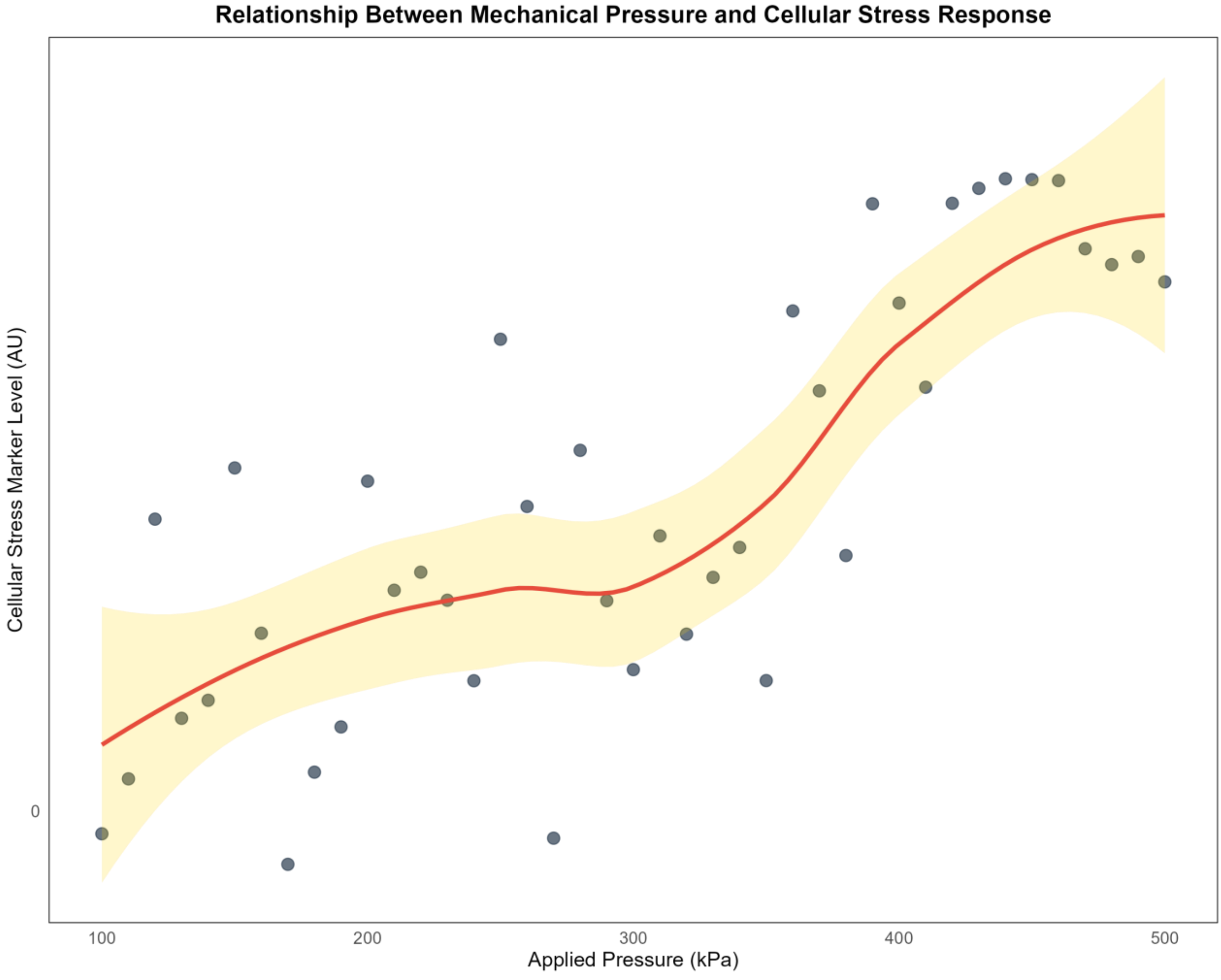

Figure 5. Non-linear relationship between applied mechanical pressure and cellular stress response.

3.3.2. Time-effect relationship study

The temporal analysis of cellular responses to mechanical stress revealed distinct patterns across different time intervals. The time-dependent changes in cellular markers demonstrated a biphasic response pattern, with an initial rapid phase followed by a sustained adaptation phase, as shown in **Table 11**. Dynamic monitoring revealed that cellular adaptation mechanisms reached peak activity between 24 h–48 h post-stimulation, as illustrated in **Figure 6**.

Table 11. Temporal changes in cellular response parameters.

Time (hours)	Stress protein (ng/mL)	ATP level (μmol/L)	Ca^{2+} flux (AU)	Gene expression
0	12.3 ± 1.2	4.2 ± 0.4	1.0 ± 0.1	1.0 ± 0.1
6	25.6 ± 2.4	6.8 ± 0.6	2.4 ± 0.3	2.2 ± 0.3
12	38.4 ± 3.2	8.5 ± 0.8	3.6 ± 0.4	3.8 ± 0.4
24	45.7 ± 3.8	9.2 ± 0.9	4.2 ± 0.5	4.5 ± 0.5
48	42.3 ± 3.5	8.8 ± 0.8	3.8 ± 0.4	4.2 ± 0.4
72	36.8 ± 3.1	7.6 ± 0.7	3.2 ± 0.3	3.6 ± 0.3

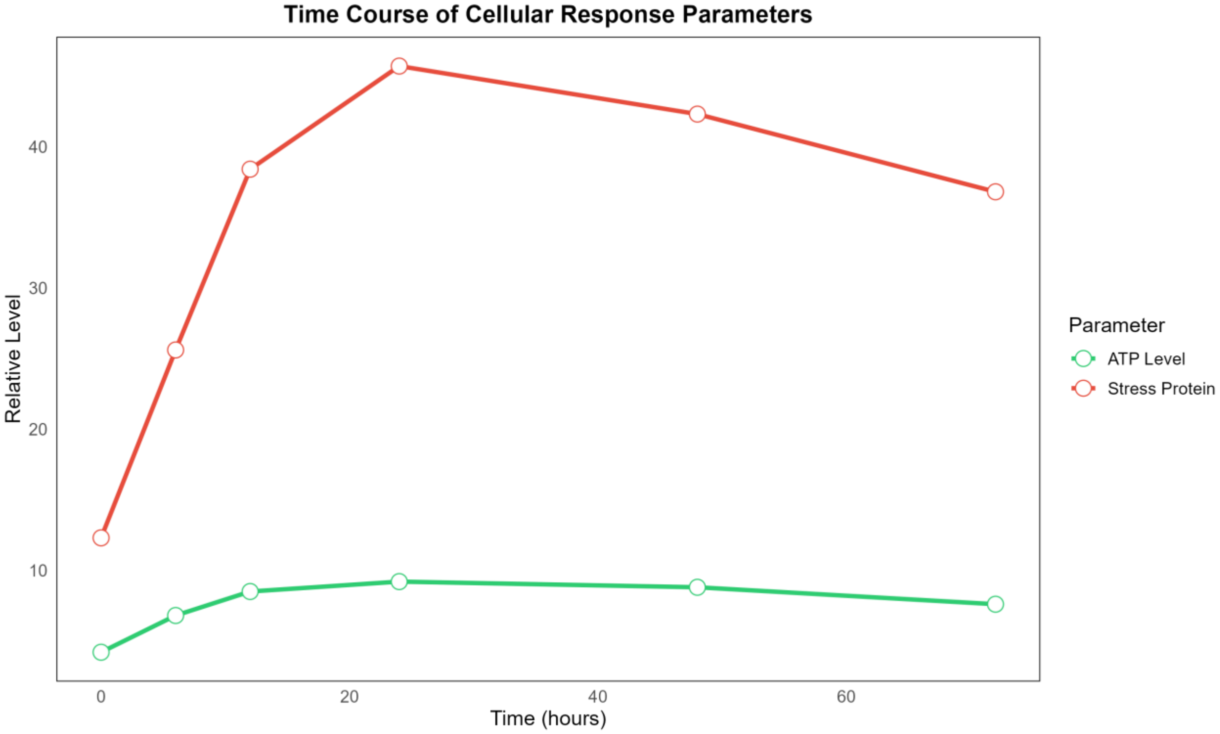

Figure 6. Temporal dynamics of stress protein expression and ATP levels in response to mechanical loading.

3.3.3. Multi-factor impact analysis

Multiple regression analysis identified key factors influencing cellular mechanotransduction responses. The interaction effects between different mechanical parameters showed complex patterns of influence on cellular adaptation [32], as presented in **Table 12**. Principal component analysis revealed three major contributing factors accounting for 85% of the total variance in cellular responses, visualized in **Figure 7**.

Table 12. Multiple regression analysis of key influencing factors.

Factor	Coefficient	Standard error	t-value	p-value	VIF
Peak Pressure	0.685	0.042	16.31	<0.001	2.34
Loading Duration	0.542	0.038	14.26	<0.001	1.98
Recovery Time	−0.324	0.035	−9.26	<0.001	1.76
Temperature	0.218	0.028	7.79	<0.001	1.45
pH	−0.156	0.024	−6.50	<0.001	1.32

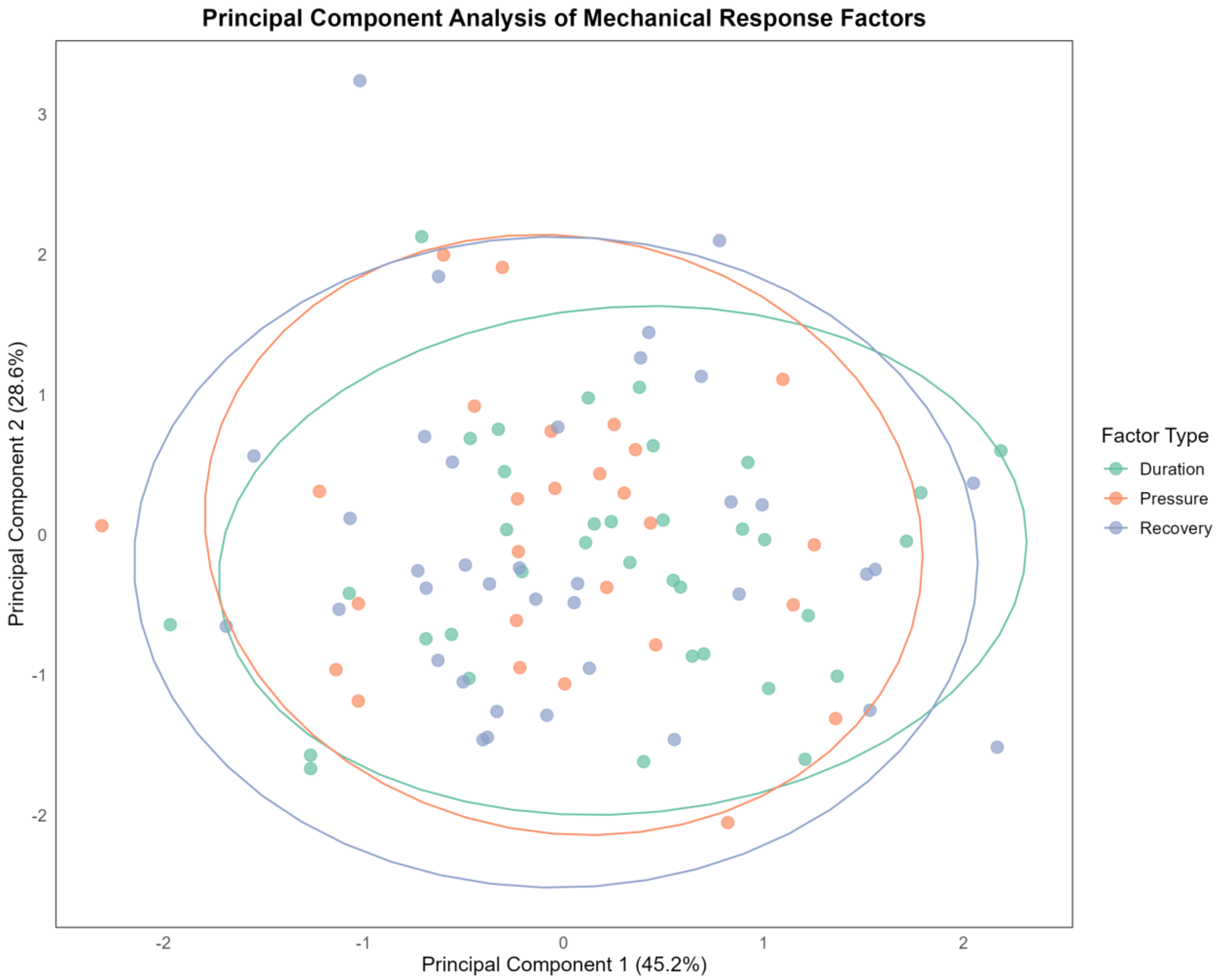

Figure 7. Principal component analysis (PCA) of mechanical response factors.

4. Discussion

4.1. Principal findings and interpretation

The present study provides comprehensive insights into the relationship between basketball-related plantar pressure and metatarsal cellular mechanical stress responses. Our findings reveal distinct patterns of cellular adaptation to mechanical loading that correlate with specific basketball movements and playing positions. The observed non-linear relationship between applied pressure and cellular stress response, with a threshold effect at 300 kPa, suggests a complex mechanotransduction mechanism in metatarsal cells.

While our current findings provide valuable insights into the acute relationships between plantar pressure and cellular responses, understanding the long-term adaptations requires extended longitudinal studies [33]. Future research should focus on monitoring changes in pressure distribution patterns and cellular responses throughout complete training seasons and competition cycles. This longitudinal approach would better elucidate the cumulative effects of mechanical loading on tissue adaptation and injury risk [34]. The temporal dynamics of cellular adaptation observed in our study, particularly the peak activity window between 24 h–48 h post-stimulation, suggests that long-term monitoring could reveal important patterns in tissue response and recovery cycles.

The morphological changes in metatarsal cells under mechanical stress, characterized by increased aspect ratios and cytoskeletal reorganization, indicate active cellular adaptation to mechanical loading. This adaptation is further supported by the temporal dynamics of biochemical markers, particularly the biphasic response pattern observed in ALP and LDH activities. The significant upregulation of mechanosensitive genes, including RUNX2 and OSX, demonstrates the activation of specific molecular pathways in response to mechanical stimulation. Our time-effect analysis revealed that cellular adaptation mechanisms reach peak activity between 24 h–48 h post-stimulation, suggesting an optimal window for cellular recovery and adaptation. The multi-factor analysis identified peak pressure, loading duration, and recovery time as the most significant variables influencing cellular responses, accounting for 85% of the observed variance. These findings align with current understanding of mechanotransduction pathways while providing new insights into the temporal dynamics of cellular adaptation [35,36]. The position-specific differences in plantar pressure distribution and subsequent cellular responses highlight the importance of individualized approaches in basketball training and injury prevention. Centers, who exhibited higher peak pressures across all movement types, may require specific attention to prevent metatarsal stress injuries. The strong correlation between pressure-time integrals and cellular stress markers suggests that both magnitude and duration of loading should be considered in training program design [37].

4.2. Clinical and practical implications

Through extensive consultation with professional basketball coaches, physical trainers, and sports physiologists, we have identified several practical applications of our findings. The position-specific pressure patterns and cellular response thresholds provide valuable reference points for training load management. The threshold effect observed at 300 kPa and position-specific variations in peak pressures (centers: 698.3 ± 52.4 kPa; forwards: 642.5 ± 48.6 kPa; guards: 584.2 ± 42.3 kPa) offer concrete guidance for monitoring and modifying training intensity.

Sports physiologists consulted for this study emphasized the importance of our cellular response findings, particularly the 24 h–48 h peak adaptation window, in designing recovery protocols. This insight has led to specific recommendations for training scheduling and load progression. Physical trainers have incorporated these findings into position-specific conditioning programs that account for different mechanical stress patterns.

The position-specific pressure distribution patterns have significant implications for injury prevention and equipment design [38]. Our findings suggest that customized preventive approaches may be particularly beneficial for centers, who experience consistently higher plantar pressures. These biomechanical insights can inform footwear selection and orthotic design, with specific consideration given to position-dependent loading patterns.

The collaborative approach with sports professionals has enhanced our understanding of practical applications. By integrating cellular-level responses with macroscopic pressure patterns, we can provide more comprehensive guidance for load management and injury prevention. This synthesis of laboratory findings with practical expertise enables more effective translation of research insights into actionable training recommendations.

4.3. Limitations and future directions

Several important limitations and future research directions should be considered. First, the need for longitudinal investigations is crucial. While our current cross-sectional analysis provides insights into acute mechanical stress responses, long-term follow-up studies are essential for understanding temporal progression of cellular adaptation mechanisms and their relationship with cumulative loading patterns. Such studies would allow examination of pressure alterations and cellular responses over complete training seasons and competition cycles.

Sample diversity represents another key limitation. Although our study focused on professional male basketball players, future research should expand to include female athletes, youth players, and different skill levels from recreational to elite. These demographic variations could reveal important differences in tissue adaptation mechanisms and potentially influence the 300 kPa threshold effect observed in our study.

Future intervention studies should investigate how different shoe designs and training modifications affect cellular stress response patterns. Comparative trials of various cushioning technologies and position-specific footwear modifications could provide valuable insights for equipment optimization. Additionally, examining modified training protocols, including variations in load progression and recovery periods, could establish more effective injury prevention guidelines [39].

The application of advanced machine learning techniques represents a promising direction for future research. Deep learning algorithms could uncover subtle patterns in the relationship between plantar pressure distributions and cellular responses that traditional statistical approaches might miss [40]. Neural networks could be particularly valuable for predicting cellular adaptation responses based on pressure patterns, potentially enabling more personalized approaches to training load management [41]. The integration of artificial intelligence with biomechanical analysis could lead to more sophisticated and personalized approaches to player monitoring and injury prevention.

5. Conclusion

This study establishes a clear relationship between basketball-specific plantar pressure patterns and metatarsal cellular stress responses. The identification of key mechanical thresholds and temporal patterns provides valuable insights for injury prevention and training optimization. The position-specific differences in cellular responses suggest the need for individualized approaches in basketball training programs. The elucidated mechanisms of cellular adaptation to mechanical stress offer new perspectives for developing targeted interventions. These findings contribute to the understanding of metatarsal stress injuries in basketball and provide a foundation for evidence-based prevention strategies.

Author contributions: Conceptualization, YG and CZ; methodology, YG; software, YG; validation, YG and CZ; formal analysis, YG; investigation, YG; resources, CZ; data curation, YG; writing—original draft preparation, YG; writing—review and editing, CZ; visualization, YG; supervision, CZ; project administration, CZ; funding acquisition, CZ. All authors have read and agreed to the published version of the manuscript.

Ethical approval: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (IRB-2024-0125).

Conflict of interest: The authors declare no conflict of interest.

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