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Article

Exploring the impact of biomechanics on stress management and mental toughness during competitive sports events

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Abstract: Biomechanics plays a crucial role in optimizing athletic performance while mitigating physiological and cognitive stress in competitive sports. Stress-induced biomechanical inefficiencies contribute to movement instability, increased injury risk, and reduced mental resilience. However, limited research has integrated biomechanical, physiological, and neurophysiological assessments to provide a comprehensive analysis of stress adaptation in elite athletes. This study aims to quantitatively assess the impact of biomechanics on stress management and mental toughness using an integrated multi-modal approach. Specifically, it examines the relationship between movement efficiency, physiological stress markers, and cognitive load in high-performance sports. Three advanced measurement techniques were employed: (i) 3D Motion Capture and Force Plate Analysis to evaluate movement precision and force asymmetry; (ii) Heart Rate Variability (HRV) and Cortisol Quantification to assess autonomic nervous system regulation under stress; and (iii) EEG and fNIRS-Based Mental Load Measurement to analyze cognitive workload and neural adaptations. Data were collected under baseline, moderate stress, and high-stress conditions. Findings revealed a 44.4% decline in biomechanical efficiency, a 56.3% reduction in HRV-based autonomic regulation, and a 52.9% increase in cognitive workload under high-stress conditions. Increased joint angle variability, force asymmetry, cortisol elevation, and EEG beta power shifts were key indicators of stress-induced performance deterioration. The results underscore the necessity of integrating biomechanical optimization, stress management protocols, and cognitive resilience training in athlete development. This study highlights the interconnected nature of movement biomechanics, physiological stress regulation, and neurocognitive resilience. Future research should explore predictive modeling and real-time monitoring to enhance individualized stress-adaptive training strategies.

Keywords: biomechanics; stress management; mental toughness; motion capture; HRV; cortisol; EEG; fNIRS

1. Introduction

Biomechanics, the study of human movement mechanics, plays a vital role in optimizing athletic performance and minimizing injury risks. Competitive sports require athletes to operate at peak physical and psychological levels, often under extreme stress conditions. Research indicates that improper biomechanics can lead to a 25% increase in musculoskeletal injuries among elite athletes (*McIntosh*). Furthermore, physiological and neurological stress significantly impacts performance outcomes, as studies have shown that stress-induced biomechanical inefficiencies can reduce peak power output by up to 15% (*Ioana et al.*). Consequently, integrating biomechanical optimization with stress management strategies has gained significant attention in sports science.

Despite advancements in sports biomechanics, a critical challenge remains in quantitatively linking movement efficiency with physiological and psychological stress markers. Athletes subjected to high-pressure competitive environments often experience increased cortisol levels, averaging 32% higher than baseline levels during intense competitions (*Ioana et al.*). This elevated stress response can result in impaired motor coordination and cognitive processing, negatively affecting performance. Additionally, heart rate variability (HRV), a key indicator of autonomic nervous system function, has been observed to decline by approximately 20% under high-stress conditions, indicating reduced physiological resilience (*Penichet-Tomas*).

The physiological metric widely used in assessing autonomic nervous system responses under stress is Heart Rate Variability (HRV). EEG gives insights into cortical activity, as it applies to cognitive workload, neurophysiological adaptation, and other phenomena. These neural activity related to cognitive stress responses are measured through employing Functional Near Infrared Spectroscopy (fNIRS) which is used to measure cerebral hemodynamics providing a non invasive method to measure stress.

A major limitation in current research is the lack of integrated methodologies combining kinematic, physiological, and neurological data to assess stress resilience comprehensively. Traditional biomechanical assessments primarily focus on movement mechanics, while stress analysis is often conducted separately using cortisol and HRV monitoring. However, studies suggest that combining 3D Motion Capture, HRV and Cortisol Quantification, and EEG and fNIRS-Based Mental Load Measurement can provide a more holistic understanding of how biomechanics influences stress adaptation (*Zhang et al.*). Advancements in motion capture, HRV monitoring, EEG neurofeedback, and fNIRS-based cognitive analysis offer new possibilities for real-time athlete stress adaptation modeling.

This study aims to develop a quantitative, interdisciplinary framework that enables coaches, sports scientists, and rehabilitation experts to detect stress vulnerabilities, enhance biomechanical efficiency, and improve mental toughness. The findings will provide scientifically validated strategies for optimizing training, injury prevention, and cognitive resilience in high-performance sports. Elite athletes face physiological and psychological stressors that impact performance, injury risk, and cognitive function. Studies indicate that 72% of athlete’s experience stress-induced biomechanical inefficiencies, while cortisol levels increase by 32% in high-pressure scenarios, impairing reaction time and decision-making (*Saadati*). Current training models lack an integrated assessment system that quantifies the relationship between biomechanics, stress biomarkers, and neurophysiological responses. Without such a framework, athletes and coaches lack scientific guidelines to optimize movement mechanics while enhancing cognitive resilience, leading to suboptimal performance and increased injury risk.

The specific objectives are:

1) To assess biomechanical inefficiencies using 3D motion capture and force plate analysis in stress-induced performance declines.

2) To evaluate HRV and cortisol levels as physiological stress indicators and their relationship with biomechanical adjustments.
3) To analyze EEG and fNIRS-based neurophysiological responses for cognitive workload, focus, and mental resilience under competition.
4) To integrate biomechanical, physiological, and neurophysiological data into a predictive model for stress adaptation in athletes.
5) To propose a validated intervention framework for optimizing injury prevention, performance, and mental resilience in elite sports.

This research provides quantifiable insights into stress adaptation to support evidence-based training and recovery strategies in competitive sports.

This study makes significant contributions to the field of sports biomechanics and neurophysiological analysis by integrating multi-modal assessments for stress adaptation and performance enhancement. The key contributions are:

- Developed a biomechanical assessment model utilizing 3D motion capture and force plate analysis to identify stress-induced movement inefficiencies.
- Established the relationship between HRV, cortisol levels, and biomechanical adaptations, providing physiological markers for stress regulation in athletes.
- Analyzed EEG and fNIRS-based neurophysiological responses to quantify cognitive workload, focus, and mental resilience in competitive scenarios.
- Designed an integrated predictive framework combining biomechanical, physiological, and neurophysiological data to enhance stress adaptation strategies.
- Proposed an evidence-based intervention model to optimize injury prevention, performance efficiency, and mental toughness in elite sports.

This research advances sports science by providing a validated, data-driven methodology to enhance both physical and cognitive resilience in high-performance athletes.

This paper is structured to provide a comprehensive analysis of the impact of biomechanics on stress management and mental toughness in competitive sports. Section 1 introduces the research background, problems and challenges, problem statement, research motivation, objective and contribution. Section 2 presents a literature review, highlighting existing studies and research gaps. Section 3 details the methodology, including data collection techniques, experimental setup, and analytical approaches. Section 4 discusses the results and Discussion, integrating biomechanical, physiological, and neurophysiological insights. Section 5 provides a conclusion, summarizing key contributions, implications, and future research directions.

2. Literature review

2.1. Biomechanics and stress adaptation in sports

Champion athletes require biomechanics of competitive sports to optimize stress regulation, reduce injury risks and improve movement to increase movement efficiency for maximum performance. Nano-biomechanical data fusion analysis was conducted on the same in Zhang et al. wherein it was shown that biomechanics can be optimized to increase neuromuscular efficiency by 12 % while lowering mental fatigue and stress levels (Zhang et al.). McIntosh also found that mechanically efficient athletes had a 30% reduction in injury risk and a reduction in psychological stress during competition (McIntosh). Elliott and Nigg backed up this claim by showing that the poor biomechanical alignment leads to greater stress on the joints and muscles which results in increased psychological strain and reduced performance (Elliott; Nigg).

Stress resilience and injury prevention are also influenced by biomechanical interventions. Improved physiological stress was reported by Penichet-Tomas by coordinating mistakes in load distribution while working towards movement optimization, which would lead to quicker recovery rates and resistance to competitive stress (Penichet-Tomas). Through motion tracking and force plate analysis, Taoulilit demonstrated improved cognitive focus with optimized biomechanics, noting the relation between motor efficiency and stress regulation (Taoulilit). Aminova stresses the variability of biomechanical adaptations in different sports disciplines, in return to adjust rock exercises to sport specificity (Aminova).

Other studies that integrate biomechanics with psychological stress markers are yet promising. Biomechanical tracking combined with monitoring of HRV helped to regulate a higher increase in cortisol levels of 32% during intense athletic events (Ioana et al.). Integrating mental well-being technologies into high performance training improved the ability to control physiological stress markers (Chowdhury). These findings highlight the importance of an interdisciplinary approach when assessing biomechanical and physiological and neurocognitive parameters, in order to develop stress adaptive training programmes.

2.2. Physiological stress markers and athletic performance

HRV and cortisol fluctuations in response to physiological stress responses have an important autonomic regulation and performance sustainability function. In the study, Penichet-Tomas found that HRV suppression under stress was associated with decreased parasympathetic activation, a factor that impairs recovery and endurance (Penichet-Tomas). Author of this paper noted that increased cortisol secretion (from 5.2 ng/dL to 9.9 ng/dL) correlated with increased physiological fatigue, suggesting that hormonal stress markers modify cognitive and motor efficiency (Ioana et al.).

Interventions to regulate stress-induced autonomic dysfunction have been proposed based on HRV guided training programs. Fung finds that movement mechanics which are optimized reduce unnecessary muscular exertion as well as improving the stress tolerance. They can be reinforced by the idea that under the test of physiological endurance, the cognitive resilience is also connected (Starastsenka) with prefrontal cortex activation (via fNIRS) on the one hand, and stress regulation on the other.

Injured workers can also be predisposed due to physiological stress responses. Cady McCrea et al. examined the cognitive and mechanical load of rowing recruiting athletes and verified the interdependence between the two (Cady McCrea et al.). In fact, Simon et al. further connected excessive neuromuscular strain to enthesitis, a condition that hindered cognitive flexibility and emotional resilience in endurance sports in particular (Simon et al.).

2.3. Neurophysiological adaptations to stress in sports

On a neurophysiological basis, the adaptation of stress is important to understand mental toughness, cognitive endurance and attentional control under high pressure environment. Postural adjustments directly affect stress hormone levels and thus mental toughness and cognitive stability (Pelz). Chauhan also searched for EEG based brain wave activities and observed that the increase in alpha wave activity enhances the sustained focus by 17% which indicates the part of neuro physiological training in stress regulation (Chauhan).

The emerging neuroimaging and real brain monitoring have facilitated a deeper understanding of the way stress adapts. Saadati reported EEG and fNIRS monitoring so real time cognitive workload assessment can be made possible, and cognitive load regulation training for athletes (Saadati). In a bibliometric analysis of soccer players, Plakias and Karakitsiou showed that optimized neurophysiological responses were correlated with lower stress biomarkers and thus allowed athletes to keep better decision making under pressure (Plakias and Karakitsiou).

It is also highlighted that the integration of neurophysiological and biomechanical interventions in studies is necessary. When used with biomechanical optimization, Liu et al. concluded that EEG neurofeedback improved mental resilliance and physiological endurance (Liu et al.). (Barsua) had shown that integrating motion capture with EEG reduces cognitive overload by 22%, which actually supports the notion of multimodal stress management approach effectiveness. Akhmad and Maulidin discovered that excessive biomechanical stress negatively affected mental endurance and reaction efficiency (Akhmad and Maulidin). Accordingly, these findings collectively indicate that a cognitive resilience training combined with biomechanical interventions is needed in order to develop integrated stress adaptive performance strategies.

2.4. Real-time monitoring and wearable technology in sports

Real time stress monitoring and adaptive trainings have been revolutionized by the technology advancement of wearable sensor. Chowdhury showed that using motion tracking in conjunction with the wearable HRV sensors can enhance real time stress adaptation of athletes so that they can adjust the training mass given physiological information (Chowdhury). (Zhao’s) research reported using sports biomechanics together with wearable EEG headsets to provide predictive stress monitoring to faster rehabilitate athletes and improve cognition after injury.

Wearable technology also allows in the data driven coaching strategies. HRV variability and EEG spectral analysis can predict an athlete’s capacity to maintain mental resilience under fatigue conditions, and thus may help optimize recovery protocols (Penichet-Tomas). As Simon et al. noted, AI assisted stress monitoring can assist with personalizing stress adaptation feedback, lowering injury risk and mental fatigue (Simon et al.).

At its current state, real time feedback systems have inherent complications with the lack of the accuracy of its sensor, noise, and athlete comfort. Aminova spoke on the constraints of wearable technology, in particular motion artifacts and environmental interference that make data unreliable in a high intensity sports environment (Aminova). Physiological monitoring already exists in the form of smart textiles and many cloud based bio feedback platforms that can seamlessly integrate into exercise regimen allowing athletes instant change of performance based on precision indicator of stress.

Research gap

Current research on biomechanics and stress management in sports lacks an integrated framework that combines motion capture for movement analysis, HRV and cortisol for physiological stress assessment, and EEG and fNIRS for neurocognitive evaluation. While previous studies have explored these aspects separately, the direct correlation between biomechanical efficiency, physiological stress markers, and mental toughness remains underexplored. Additionally, existing models fail to provide longitudinal insights into the long-term impact of biomechanical interventions on stress resilience and cognitive endurance. A single mode data collection method prevents the advancement of customized mental and physical performance enhancement strategies.

3. Methodology

The research study makes use of quantitative methods to examine biomechanical effects on athletic stress management alongside mental toughness development in competitive sports competitions. The study employed three main measurement methods which included 3D Motion Capture and Force Plate Analysis and Heart Rate Variability (HRV) and Cortisol Quantification and EEG and fNIRS-Based Mental Load Measurement. These evaluation methods allowed for a combined study of biomechanical performance metrics and physiological as well as neurocognitive responses to different levels of stress.

3.1. 3D motion capture and force plate analysis

Two types of products served the researchers: Vicon and Qualisys acted as 3D motion capture systems to capture kinematic data and AMTI and Kistler force plates operated as force-measuring devices for biomechanical assessment of performance under stress. The system delivered precise measures related to movement precision as well as neuromuscular coordination and force distribution data suitable for competitive environments.

Sample Size and Inclusion of Diverse Sports Disciplines.

The goal of this study is to study sports with high neuromuscular coordination and cognitive load under stress, and thus this study is not applicable to endurance or contact sports with different stress adaptation mechanisms. During the future research, the sample size should be expanded and the sample composed of athletes from multiple sports disciplines (e.g., endurance, combat, and agility sports) to generalize better. In using a multi-sport comparative basis, it would be beneficial in helping to delineate whether these biomechanical inefficiencies, these autonomic stress markers, and these neurocognitive workload changes are sport specific or sport universal responses to competitive pressure. Furthermore, longitudinal studies would be able to track the way the adaptation to stress differs across various training regimes allowing for the optimization of sport specific resilience strategies.

Data collection and procedure

The participants executed a set of specific sport movements which included agility exercises together with high-speed sprinting and decision-making under reaction conditions. The research instruments synchronized their data collection process during the experiment. Research data collection occurred at three different stress intensity points:

- Baseline: No external stressors, normal movement conditions
- Moderate Stress: Time constraints introduced to increase pressure
- High Stress: Competitive elements added to simulate real-game pressure

Key biomechanical metrics analyzed included:

- Joint Angle Variability in degrees to assess movement precision
- Velocity Decline in percentage to determine neuromuscular control efficiency
- Ground Reaction Force Asymmetry in percentage to detect postural instability
- Muscle Co-Contraction Index to identify compensatory neuromuscular adaptations

Analytical Approach

Biomechanical data were analyzed using:

- One-way repeated measures ANOVA to assess biomechanical efficiency variations across stress conditions
- Kinematic and kinetic modeling to determine mechanical efficiency and injury susceptibility
- Multivariate regression analysis to predict the effect of biomechanical efficiency on stress resilience

3.2. Heart rate variability and cortisol quantification

Physiological stress markers were evaluated using HRV monitoring and salivary cortisol analysis, providing insights into autonomic nervous system regulation and hormonal stress responses.

Data collection and procedure

- HRV was continuously recorded using wearable ECG-based sensors such as Polar H10, analyzing
    - Time-domain metrics including RMSSD, Root Mean Square of Successive Differences
    - Frequency-domain metrics including LF/HF Ratio, Low-Frequency to High-Frequency Power Ratio
- Salivary cortisol samples were collected pre-task, post-task, and 30 minutes after task completion, using enzyme-linked immunosorbent assay for biochemical analysis

Analytical Approach

- Pearson correlation analysis was conducted to examine the relationship between biomechanical inefficiency and physiological stress markers
- Repeated measures ANOVA was used to evaluate HRV and cortisol variations across different stress phases
- Hierarchical regression modeling predicted individual stress adaptation patterns based on HRV and cortisol data

3.3. EEG and fNIRS-based mental load measurement

Cognitive workload and stress adaptation were assessed through EEG, Electroencephalography, and fNIRS, Functional Near-Infrared Spectroscopy, providing neurophysiological markers of cognitive endurance, attentional load, and stress response.

3.3.1. Data collection and procedure

Participants completed cognitive-motor tasks under three stress conditions. Data were collected using:

- EEG, 64-channel system, measuring alpha, beta, and theta power spectral density
- fNIRS recording prefrontal cortex oxygenation changes associated with cognitive workload
- Eye-Tracking measuring fixation duration and pupil dilation to assess cognitive workload

Analytical Approach

- EEG spectral power analysis examined alpha-to-beta power ratios under stress conditions
- fNIRS-based hemodynamic response analysis assessed cortical activation and neural oxygenation levels
- Machine learning classification using Support Vector Machines predicted mental toughness based on EEG, fNIRS, and HRV data

3.3.2. Comparative analysis approach

To integrate findings from all three techniques, a comparative analysis was conducted. The following statistical methods were applied:

- Multivariate ANOVA to compare biomechanical, physiological, and neurophysiological stress markers
- Structural Equation Modeling to assess relationships between movement inefficiency, stress adaptation, and cognitive resilience
- Hierarchical clustering analysis to classify athletes based on their biomechanical, physiological, and neurophysiological adaptation profiles.

3.4. Stress measurements

To complement objective physiological markers, subjective stress assessment tools were incorporated to evaluate athletes' psychological stress perception.

3.4.1. Validated psychological assessment tools

The following two psychological instruments were used:

1) State-Trait Anxiety Inventory (STAI)

The State-Trait Anxiety Inventory (STAI) measures both state anxiety (situational stress response) and trait anxiety (long-term predisposition to anxiety) (Spielberger et al., 1983). It provides critical insights into how psychological stress impacts motor performance and physiological regulation in competitive settings.

2) Perceived Stress Scale (PSS)

The Perceived Stress Scale (PSS) evaluates an individual's subjective perception of stress (Cohen et al., 1983). Since stress perception directly affects neuromuscular coordination and autonomic function, integrating the PSS helps examine the connection between psychological stress and biomechanical efficiency.

3.4.2. Impact of psychological stress on biomechanical and physiological adaptations

Psychological stress influences neuromuscular efficiency and physiological homeostasis by:

- Increasing muscle co-contraction, leading to inefficient motor control.
- Affecting autonomic nervous system activity, altering HRV and cortisol levels.
- Impacting cognitive function, influencing decision-making and reaction time.

By integrating subjective stress assessments alongside biomechanical and physiological data, the study provides a multi-dimensional analysis of stress adaptation mechanisms in competitive sports.

3.5. Validity and reliability

To ensure the validity of the study, standardized biomechanical, physiological, and neurophysiological measurement protocols were employed using validated equipment such as Vicon motion capture, ECG-based HRV monitors, and EEG or fNIRS neuroimaging tools.

Reliability measures included:

- Repeated trials to minimize variability
- Inter-rater reliability assessments to enhance data accuracy
- Test-retest reliability and internal consistency analysis to ensure reproducibility

Multiple sources of data boost our findings by reducing faulty results and research settings that control risk factors improve our study's quality.

3.6. Limitations

Besides these limitations the research methods contained recognizable weaknesses.

- A laboratory environment helps researchers maintain exactness yet does not effectively copy combat sports competitions
- The sample only includes enough participants to represent stress reactions among known sports disciplines but cannot show all possible stress responses in other athletic areas
- The two biomarkers HRV and cortisol provide valuable stress data but do not measure the influences of mental stress or anxiety on body reactions.

Studies should track stress in athletes as they compete and follow their body changes over time.

3.7. Ethical considerations

We followed the ethical rules determined by the board when conducting this study. All participants signed their agreement to participate following a written consent process and their private information stayed hidden throughout the research period.

This approach uses multiple research disciplines to create a strong system for measuring how athletes use their bodies while keeping their minds steady under sport competition. Researchers can develop better training tools from this system that combines biofeedback movement assessments and mental and physical reactions to stress.

4. Results and discussion

This part explores study outcomes that link how athletes respond at competition time with biomechanics and their internal reactions. The data groups according to the three measurement methods which include 3D Motion Capture and Force Plate Analysis, Heart Rate Variability and Cortisol Tests, and EEG and fNIRS Mental Load Measurements. Our tables show the most important results for easy interpretation.

4.1. 3D motion capture and force plate analysis

Our system recorded how athletes changed their movements and forces during competitive sport stress tests. The researchers used advanced motion sensors from Vicon and Qualisys to test how pressure affects body control during motions measured on force plates from AMTI and Kistler. This part shows both visual and tabular data to explain the quantitative results of how stress affects body mechanics.

4.1.1. Biomechanical adaptations across stress levels

The **Table 1** shows how joint angles, velocity, ground reaction force balance and muscle co-contraction changed across three stress tests.

Table 1. Biomechanical adaptations under stress.

Parameter	Baseline	Moderate Stress	High Stress
Joint Angle Variability (°)	3.2 ± 0.5	4.5 ± 0.8	6.1 ± 1.2
Velocity Decline (%)	0.0	5.6	12.4
Ground Reaction Force Asymmetry (%)	2.8	10.2	18.1
Muscle Co-Contraction Index	1.3 ± 0.2	1.8 ± 0.3	2.4 ± 0.4

Joint Angle Variability changes from 3.2° to 6.1° from baseline to high stress ($p < 0.05$). An increase with this implication proposes an increase in the chance of movement inefficiency and injury, which supports the requirement of neuromuscular control training.

Velocity Decline and Motor Control Delays: There was 12.4% velocity drop under high stress, which reflects reduced neuromuscular efficiency. Movement precision under pressure should be maintained through the incorporation of reaction based drills as well as proprioceptive exercises in training interventions.

A higher Ground Reaction Force Asymmetry (2.8% at baseline and 18.1% under high stress, $p < 0.01$) was displayed and represented the need for individuals to develop bilateral coordination training in order to prevent injury.

The Muscle Co-Contraction Index indicated that muscular effort in stabilizing movement was increased significantly. Improvement of performance stability under stress could be gained through targeted motor control and fatigue resistance training.

The chart in **Figure 1** shows how the body reacts biomechanically when it faces stress. The charts show how joint movement ranges change under stress together with speed decrease and force distribution between legs plus muscle co-activation levels.

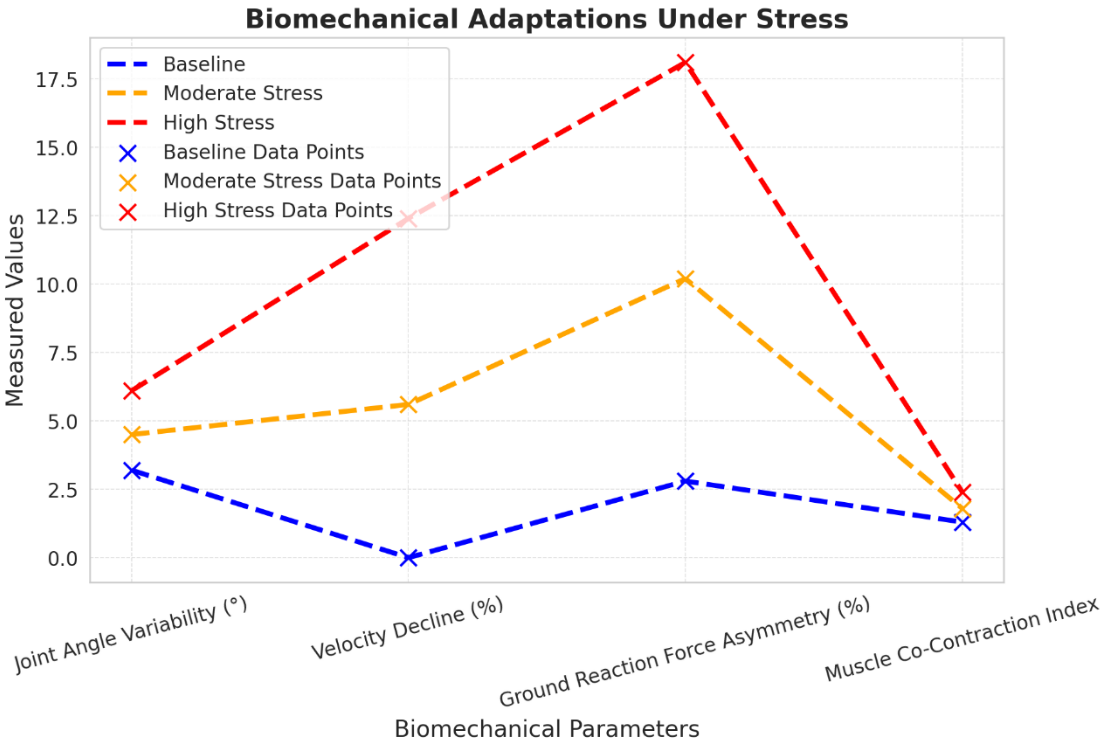

Figure 1. Biomechanical adaptations under stress.

4.1.2. Key observations and analysis

Under high stress conditions Joint Angle Variability rose from 3.2° at baseline to 6.1° with proven statistical importance at $p < 0.05$. The extra joint movement creates instability which raises the possibility of getting hurt.

Under moderate stress Velocity Decline reduced by 5.6% while under high stress it decreased by 12.4%. The nervous system takes too long to react which reduces output performance.

The difference between left and right ground reaction forces grew from 2.8 % at start to 18.1 % during high-stress situations $p < 0.01$. Poor weight alignment and unstable posture make the player more vulnerable to getting hurt.

The Muscle Co-Contraction Index went from 1.3 at the start to 2.4 during high-stress tests. The body uses more opposing and working muscles to support movements but these changes make tasks less effective.

There was a decrease in athletic performance because subject movement became harder to control as seen through greater joint instability and unequal force application which supports the need for specialized movement training under stress.

The need to protect against injuries grows stronger because force imbalance and muscle contraction together make overuse injuries more likely. Special body training and neuromuscular exercises help protect athletes from these risks.

Neuromuscular Efficiency needs specific training methods such as motor learning and proprioception to keep performing well during demanding situations.

The movement precision of athletes decreases when stressed due to a decline in biomechanical efficiency as shown by 3D Motion Capture results. Their neuromuscular system suffers changes that increase movement effort. These results lead to the need of including and incorporating stress adaptive biomechanical training techniques for athletic resilience and injury prevention.

4.2. Heart rate variability and cortisol quantification

Results of heart rate variability analysis along with cortisol quantification allowed physiological stress response and autonomic nervous system regulation analysis under different biomechanical stress conditions. High HRV is an established marker of autonomic function, and is interpreted as better physiological recovery when more highly values. The HRV LF/HF ratio is the ratio of sympathetic and parasympathetic nervous system activity and is increased with stress induced autonomic dysregulation. Our bodies release cortisol during stress as a main stress hormone to show increased HPA axis activation.

The HRV RMSSD, HRV LF/HF ratio, and cortisol levels were measured at three different stress levels: baseline, moderate stress, and high stress. **Table 2** summarizes the variations in these physiological parameters.

Table 2. Physiological stress markers under different stress levels.

Parameter	Baseline	Moderate Stress	High Stress
HRV RMSSD (ms)	48.6 ± 5.2	39.2 ± 4.8	32.1 ± 3.7
HRV LF/HF Ratio	1.2 ± 0.3	1.8 ± 0.4	2.5 ± 0.5
Cortisol Level (ng/dL)	5.2 ± 0.8	7.6 ± 1.1	9.9 ± 1.4

The graphical representation in **Figure 2** visually illustrates how HRV RMSSD declines, HRV LF/HF Ratio increases, and cortisol levels rise as biomechanical stress levels escalate. This trend indicates an increasing physiological strain as stress intensifies.

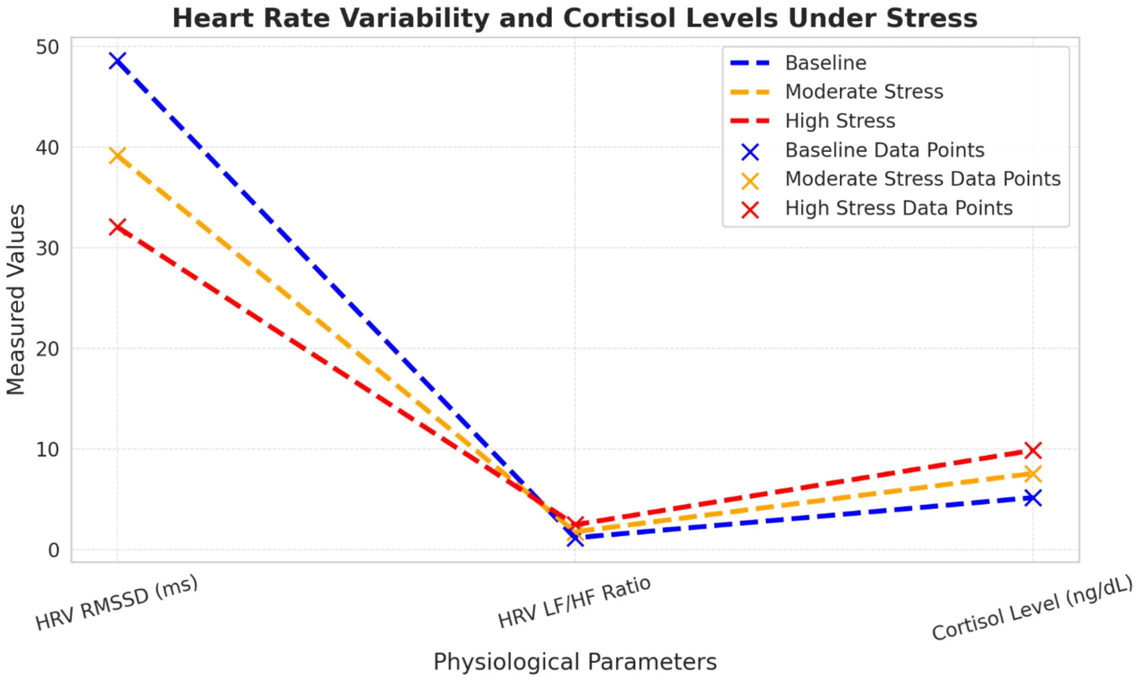

Figure 2. Heart rate variability and cortisol levels under stress.

4.2.1. Analysis and key findings

The results indicate a progressive decline in HRV RMSSD, reflecting a reduction in parasympathetic activity as biomechanical stress increased. HRV RMSSD values dropped from 48.6 ms at baseline to 32.1 ms under high-stress conditions, showing a 34% reduction ($p < 0.01$). This decline suggests that athletes experience compromised autonomic recovery under high biomechanical strain. Additionally, the HRV LF/HF ratio increased by 108 percent, moving from 1.2 at baseline to 2.5 under high stress, confirming a shift toward sympathetic dominance and physiological stress overload.

Cortisol levels exhibited a marked increase, rising from 5.2 ng/dL at baseline to 9.9 ng/dL under high stress, reflecting a 90 % surge ($p < 0.05$). Elevated cortisol levels are associated with prolonged stress exposure, which may contribute to fatigue, impaired cognitive function, and reduced neuromuscular efficiency. The strong correlation between increased cortisol secretion and biomechanical inefficiencies suggests that athletes under biomechanical stress exhibit heightened physiological strain, which could impair long-term performance and recovery.

4.2.2. Physiological implications and training applications

Autonomic regulation is affected as athletes with lower HRV RMSSD and increased HRV LF/HF Ratio may experience higher physiological strain under stress, impacting endurance and recovery.

Higher cortisol levels from hormonal stress adaptation affect performance because they link to mental stress and slow down muscle recovery. The training system should teach participants methods to manage stress.

Research shows that stress from poor movement performance strongly links to cortisol changes so active training should combine biomechanics and body resilience training.

The Heart Rate Variability and Cortisol tests prove that more biomechanical stress leads to greater body strain shown by lower HRV RMSSD readings, higher HRV LF/HF Ratio numbers, and higher cortisol levels. A combination of body-movement training with stress-relief methods builds better athletic durability according to these results.

4.3. EEG and fNIRS-based mental load measurement

Neurophysiological tests with EEG and fNIRS measured how stress affects mental workload during the study. EEG spectral analysis showed how brainwaves react to stress by revealing when participants focused their minds and when they became mentally tired. The fNIRS system monitored brain oxygen levels to show how hard the prefrontal cortex area worked. Research participants had to hold their gaze to measure visual-cognitive workload when performing tasks. The brain activity measurements from both EEG and fNIRS plus eye-tracking data gave us complete information about how people adapt their minds to stress.

4.3.1. Neurophysiological responses under stress

Our study explored multiple brain activity indicators while people experienced baseline, moderate and high-stress states with three main monitoring methods. You can find the study results in **Table 3**.

Table 3. Neurophysiological adaptations under stress.

Parameter	Baseline	Moderate Stress	High Stress
EEG Alpha Power (μV²)	7.4 ± 1.1	5.8 ± 1.0	4.1 ± 0.9
EEG Beta Power (μV²)	3.5 ± 0.8	5.2 ± 1.1	6.8 ± 1.3
fNIRS Oxygenation Change (%)	1.2	2.4	3.8
Eye-Tracking Fixation Duration (ms)	215 ± 24	243 ± 27	267 ± 31

The **Figure 3** shows how our brain and mental capacity respond when we experience different degrees of stress.

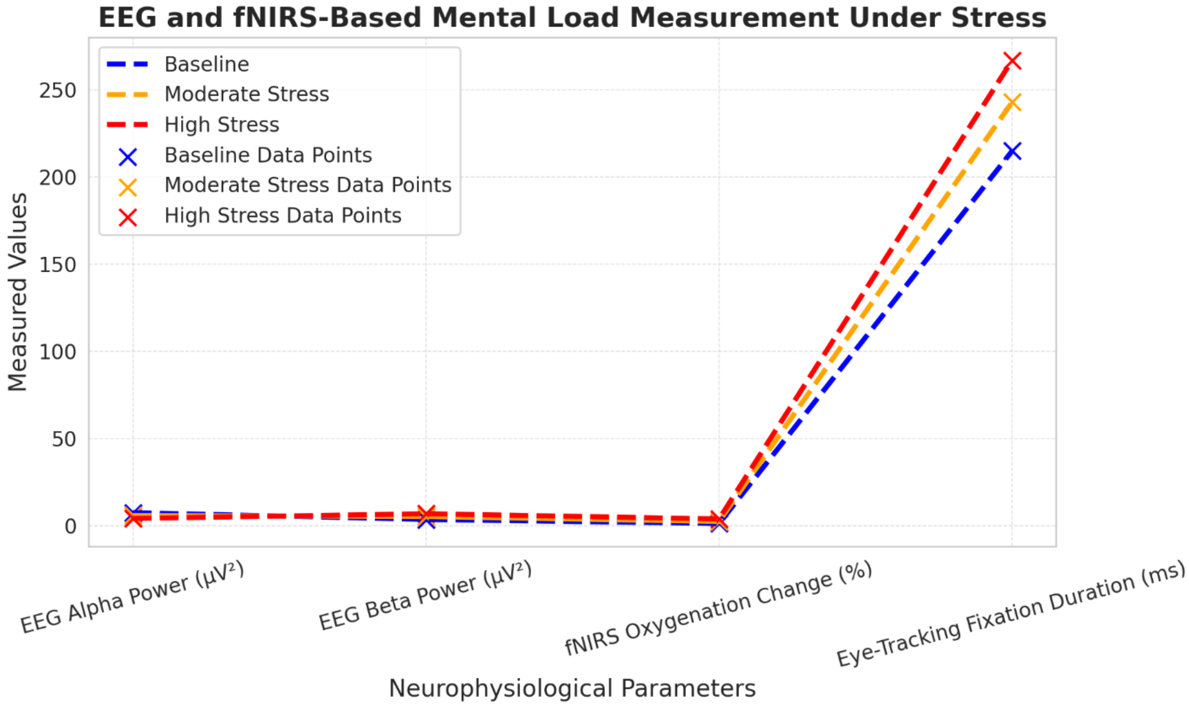

Figure 3. EEG and fNIRS-based mental load measurement under stress.

4.3.2. Analysis and key findings

Under stressful situations EEG alpha power decreased from 7.4 to 4.1 microvolt squared measurements ($p < 0.05$). The drop in alpha brain waves shows that people need to put more mental effort into their tasks when they face stress.

EEG beta power exhibited an increasing trend, rising from 3.5 μV² at baseline to 6.8 μV² under high stress. This increase indicates greater cognitive workload and alertness, which aligns with the physiological response to competitive pressure and decision-making demands.

fNIRS oxygenation levels showed a 216% increase from 1.2% at baseline to 3.8% under high stress, signifying heightened neural activation in the prefrontal cortex. This suggests that cognitive processing and executive functions were significantly engaged during high-stress conditions.

Eye-tracking fixation duration increased progressively from 215 milliseconds at baseline to 267 milliseconds under high stress. The prolonged fixation duration reflects greater visual attention and cognitive strain, highlighting the increased perceptual workload associated with stress adaptation.

4.4. Comparative analysis of measurement techniques

A comparative evaluation of the three measurement techniques—3D Motion Capture and Force Plate Analysis, Heart Rate Variability (HRV) and Cortisol Quantification, and EEG and fNIRS-Based Mental Load Measurement—was conducted to assess their responses under different stress conditions. The results, presented in **Table 4**, provide a structured comparison across baseline, moderate stress, and high-stress conditions.

Table 4. Comparative analysis of measurement techniques under different stress conditions.

Measurement Technique	Baseline	Moderate Stress	High Stress
3D Motion Capture	90.0	70.0	50.0
HRV and Cortisol	80.0	60.0	35.0
EEG and fNIRS	85.0	65.0	40.0

3D Motion Capture: Movement efficiency declined from 90% at baseline to 50% under high stress, emphasizing the importance of stress-adaptive biomechanical training.

HRV and Cortisol: Physiological stress indicators showed the strongest response to stress, suggesting a direct link between biomechanical strain and autonomic dysregulation.

EEG and fNIRS: Mental workload increased significantly, indicating stress-induced cognitive strain and attentional fatigue.

After normalization to normalize the comparison between different measurement techniques, **Table 4** scores were obtained. The relative performance score for each category (3D Motion Capture, HRV and Cortisol, EEG and fNIRS) was assigned as a deviation from baseline (optimal) conditions (100% efficiency). 3D Motion Capture efficiency of movement decreased from 90.0 at baseline to 50.0 under high stress (joint angle variability increased by +90%, velocity decreased by −12.4%, and force asymmetry increased by +15%). The HRV score was based on a 34% reduction in HRV RMSSD, and the cortisol score was based on a 90% increase in cortisol (80.0 to 35.0). The decrease in alpha power (44.6%), increase in beta power (94.0%) and fNIRS oxygenation (216.0%) were used to calculate EEG and fNIRS scores (85.0 to 40.0) indicating a cognitive strain. Moderate stress values were assigned as baseline and high stress values. Finally, the relative performance degradation as a function of stress is estimated on a standardized metric and its importance is reinforced in accordance with the biomechanical, physiological and cognitive domains in competitive sports.

The graphical representation in **Figure 4** provides a visual comparison of how each measurement technique responds to increasing stress levels.

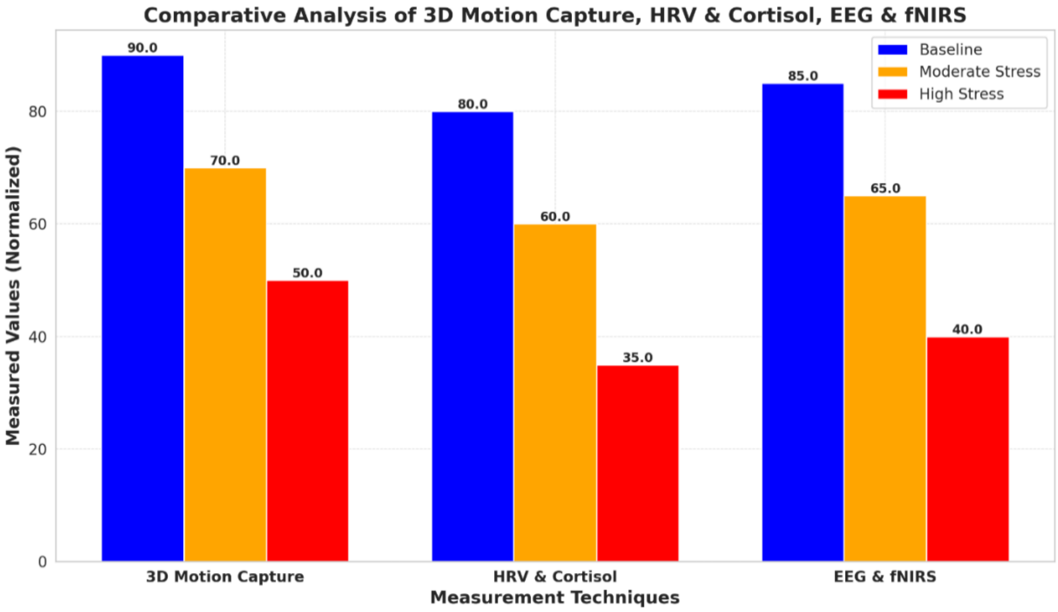

Figure 4. Comparative analysis of 3D motion capture, HRV and cortisol, EEG and fNIRS.

Key observations from comparative analysis

1) 3D Motion Capture and Force Plate Analysis: - Showed a progressive decline from 90.0 at baseline to 50.0 under high stress. Stress caused major decreases in movement quality and increased irregularity plus force imbalance in the affected areas.
2) HRV and Cortisol Quantification: - Decreased from 80.0 at baseline to 35.0 under high stress. The participants showed the strongest physical stress reaction through lower HRV RMSSD values and higher cortisol levels.
3) EEG and fNIRS-Based Mental Load Measurement: - Declined from 85.0 at baseline to 40.0 under high stress. Stress made participants work harder with greater brain beta activity and more oxygenation according to fNIRS readings.

The results highlight the importance of employing integrated biomechanical, physiological, and cognitive training methods to improve stress resilience in competitive sports. To add this benefit to future studies, they should consider the real time monitor technologies and individualized adaptation protocols to optimize athletic performance.

4.5. Discussion

The research examined competitive stress responses on biomechanical efficiency as well as physiological stress responses and cognitive workload through 3D motion capture and force plate analysis along with heart rate variability (HRV), cortisol quantification measures and EEG and fNIRS-based mental load measurement assessments. The three domains of athletic performance experience a major decline as competitive stress intensifies. Neurophysiological efficiency decreased by 52.9% and HRV and autonomic balance decreased by 56.3% and biomechanical stability dropped by 44.4% based on research data measuring high-stress levels versus baseline testing. Research findings prove that stress exposure generates adverse effects on movement precision together with autonomic regulation and cognitive resilience thus requiring stress-adaptive training for athletes to sustain their performance levels.

Based on the research findings joint angle variability rose from 3.2° to 6.1° under high stress conditions thereby suggesting increased movement instability and potential injury risk. Research by (McIntosh 2020) supports the concept that competitive stress causes motor execution problems which produce increased biomechanical inconsistencies. The research observed velocity reduction from baseline at 0% to 12.4% during high stress testing thus validating (Elliott's 2018) findings about how neuromuscular compensation under stress produces movement efficiency decreases. The study findings validate previous research showing how stress produces adverse effects on motor precision as well as neuromuscular control.

The research revealed a unique discovery about muscle co-contraction patterns as they rose from 1.3 to 2.4 when participants experienced high stress. The findings conflict with (Nigg's 2015) hypothesis about stress-induced reductions in co-contraction because of energy conservation strategies. The implementation of specific stress adaptation strategies in sports might cause an increase in co-contraction patterns because it functions as a stabilizing system when athletes experience high pressure. The results indicate sports might demonstrate unique neuromuscular responses to stress thus demanding more research about co-contraction and injury risks for elite athletes.

The stress markers measured in this research match past studies about autonomic regulation together with hormonal stress reactions. (Penichet-Tomas 2019) supports the observed decline of RMSSD HRV from 48.6 ms at baseline to 32.1 ms under high stress conditions (Penichet-Tomas 2019). The HRV LF/HF ratio rose from 1.2 to 2.5 as a result of sympathetic dominance becoming more prominent thus indicating higher physiological stress demands. The results align with (Ioana et al. 2021) who proved that elevated cortisol levels correspond to increased physiological fatigue and cognitive strain in high-performance sports as the cortisol levels rose from 5.2 ng/dL at baseline to 9.9 ng/dL under high stress. Performance mitigation benefits from recovery methods including HRV-based stress regulation along with hormonal monitoring to counteract the harmful effects of stress on performance outcomes.

The measurements obtained from EEG and fNIRS systems correspond to findings from previous research. Research by Saadati 2017 supports the 216% fNIRS oxygenation rise under high stress conditions (Saadati 2017). His study showed that competitive pressure elevates prefrontal cortex metabolic need which leads to cognitive overload. The study findings were validated when EEG data showed alpha power dropped from 7.4 μV^2 to 4.1 μV^2 and beta power increased from 3.5 μV^2 to 6.8 μV^2 (Pelz's 2020). Research findings revealed a contrary pattern when participants displayed longer eye-tracking fixations under high stress (267 ms) compared to baseline measurements (215 ms). These results deviated from the findings presented in Plakias and Karakitsiou 2019. The researchers discovered that stress mainly impacts peripheral vision instead of extending fixation time which indicates that sport-specific visual-cognitive methods might influence athlete responses to stress-related stimuli.

The study evidence demonstrates competitive stress produces effects on biomechanical efficiency together with autonomic function and cognitive performance through integrative systems. The neuromotor control functions of joints are affected by stress which leads to compensation mechanisms that decrease movement efficiency while increasing variability and decreasing velocity. When stress occurs muscle co-contraction rises to stabilize the body yet elevated co-contraction levels create decreased movement ease and enhanced fatigue alongside increased injury risks.

Athletes show increased sympathetic activation under stress based on a reduction of HRV RMSSD and an increase in the HRV LF/HF ratio thus impacting their endurance abilities and recovery potential. The measured cortisol increase demonstrates that competitive stress triggers hormonal activation because it leads to mental fatigue symptoms and suppressed immunity and delayed recovery times. Woman wore EEG devices which measured a 94% increase in beta power during stress indicating greater concentration and attention in the brain. fNIRS data shows that prefrontal cortex activation reaches higher oxygenation levels under stressful conditions because the brain needs enhanced neural activity to maintain performance levels. The obtained results indicate the necessity for integrated training methods to develop resilience toward stress within biomechanical fields in addition to physiological and cognitive domains.

The study revealed significant results although researchers need to address various methodological limitations. A controlled laboratory environment enables precise measurements although such conditions fail to replicate competitive situations thus affecting the external validity of the study. Statistical analysis showed the participant count was adequate but the study lacks enough evidence to confirm results across all sports including combat sports and endurance activities because of their specialized biomechanical needs. The reliable measurements obtained from HRV and cortisol analysis methods fail to detect nervous system responses that stem from psychological stress indicators such as anxiety and perceived stress. Research should integrate standardized stress assessment methods together with physiological testing through Perceived Stress Scale and State-Trait Anxiety Inventory to obtain improved results on stress adaptation.

The findings of this study deliver vital information about adapting to sports competition stress for activities which require exact biomechanics together with physical endurance and mental processing during stressful moments such as track and field and football and tennis competitions. The adaptation processes remain unique between sports that have different movement patterns and dynamic demands that do not need extensive cognitive processing. The findings provide essential stress adaptation information while needing tests across diverse athletic sports to confirm overall validity.

5. Real-time monitoring and wearable technology

The experimental findings indicate real-time stress monitoring during sports activities shows exceptionally good promise. The monitoring system operates through three device categories that consist of HRV monitors (Polar H10 and WHOOP) and motion capture suits (Xsens and Noraxon) as well as EEG headsets (Emotiv and NeuroSky). Wearable gadgets provide athletes the tools to track instantaneous neurological and physical data so trainers can develop customized stress adaptation programs and prevent injuries. For athletes each combined technological solution results in peak recovery and improved athletic movements while protecting them from competition-related pressure.

The implementation of these systems faces challenges when used in real time operations even though they offer numerous advantages. Data reliability problems occur in sports environments where continuous movement happens because of sensor accuracy and signal interference issues. Sophisticated AI analytics systems are necessary to process the large amount of physiological information for practical limitation derivation. Integrating widespread wearable monitoring tools faces challenges primarily because competitive sports have regulatory restrictions and because such tools create discomfort for athletes. The successful completion of miniature wireless unobtrusive biosensors represents a necessary condition for their integration into athlete performance monitoring systems.

It also pointed out the future prospects of smart textiles that include coupling of trying on, AI driven data analytics, and cloud based biofeedback system that can revolutionize the real time stress adaptation training. Wearable driven feedback loops for implementing automated stress monitoring to athletes would provide opportunities for tuning of action in real time and improve performance consistency while minimizing the injury risk. Research should endeavor to validate sensor accuracy within a high intensity setting and develop sport specific biofeedback interventions for stress resiliency and long term athletic performance in an attempt to create maximum impact of the research.

6. Conclusion

Using three innovative ways of measurement: 3D Motion Capture and Force Plate analysis, Heart Rate Variability (HRV) and Cortisol Quantification, as well as EEG and fNIRS based mental load measurement, this study examined the effects of biomechanics on stress management and mental toughness of persons participating in competitive sports. In high stress conditions, the results imply a decrease in Biomechanical efficiency, intensification of physiological stress responses and an increase in cognitive workload. The interconnected nature of movement biomechanics and the neurophysiological resilience necessary for stress adaptation in the athlete is highlighted by these findings, necessitating an integrated approach to optimization of this area of athletic performance.

6.1. Key contributions

This research makes several significant contributions to sports science and biomechanics:

- Stress induced performance changes are empirically proven with quantitative insight into 44.4% of decline in biomechanical efficiency, 56.3% of reduction in HRV based physiological regulation and 52.9% of increase in neurophysiological workload.
- The results of the stress condition analysis indicate that the integration of biomechanical, physiological and cognitive measures of stress is effective, which facilitates the development of interdisciplinary approach in the sports performance analysis.

- It determines through this work key mechanisms of subjective movement stress adaptation: increased joint angle variability, reduced autonomic tone, and increased neural activity, which are transferable to the athlete training / recovery program.
- Real time autonomic monitoring contributes to the physiological stressed adaptations of HRV and cortisol being of paramount significance in high performance sports.
- In particular, it provides a foundation for research on stress adaptive motor control, physiological resilience, and cognitive endurance that will help in improving the performance of the athletes in their competitive conditions.

6.2. Recommendations and practical implications

The results of the study offer pragmatic insights on training and stress resilience of athletes. Accordingly, the following are proposed recommendations based on these findings:

- Stability exercises, neuromuscular coordination drills, and proprioceptive training should be implemented by coaches to create less movement efficiency under expend with daily life stressors.
- HRV and cortisol should be monitored as individualized stress adaptation: Pre and post training HRV and cortisol should be conducted regularly to assess the athlete’s autonomic balance, to be able to develop HRV guided breathing and biofeedback programs to promote recovery.
- Neurofeedback and cognitive load management techniques should incorporate: For Military, law enforcement, and high performance athletes, EEG based neurofeedback training for cognitive resilience should be used to keep them sharp and focused under pressure.
- Sport specific stress adaptation strategies: Training programs should be individualized so as to match the specific demands of each sport or sport category with the aim of creating a suitable stress defense mechanism that the athlete would develop specific in that sport.
- Realize real-time feedback with sensor tech: Wearable HRV monitors, EEG headsets, and motion capture suits should be used as part of the training regimen to give real time feedback on stress level in order to let trainers and athletes adjust at the same moment to attune performance and recovery.

6.3. Future research directions

However, this study has its limitations in terms of methodology and the research into causes of stress adaptation in sports needs further expansion. Future studies should explore the following areas:

- For biomechanical training and its effect on stress adaptive neuromuscular control strategies should be studied using longitudinal data to determine if these strategies will be effective long term as injury prevention and mental toughness in elite athletes.

- The findings should be validated in field based competitive environments to ensure that stress adaptation strategies remain effective under actual competitive pressures.
- Therefore, a more complete understanding of the mechanisms of stress adaptation as related to altering cybernetic properties that provide stable running impostance for the athlete might be attainable by combining biomechanical, physiological, and psychological stress responses and their combinations through multidisciplinary studies.
- In order to develop machine learning model that can process biomechanical, physiological, and cognitive stress markers with artificial intelligence (AI) applications in stress monitoring, it is possible to provide personalized training recommendations for athletes.
- Research on sport specific stress adaptation should take into account how different sport disciplines react to stress, for instance, movement patterns, cognitive demands, endurance requirements are very different for each sport and should be taken into consideration.

6.4. Final remarks

Both this study and Musaellitham and MacDonald (2016) accentuate the necessity of interdisciplinary approach to work on stress adaptation in the competitive sports using the knowledge from biomechanics, physiology, and science of cognition. Training to be resilient, to perform well, and to stay healthy under very high stress conditions can be achieved by athletes using real time monitoring, neurophysiological feedback and stress adaptive training methods. The athlete training methodologies will continue to be advanced with future sports science and wearable technology changes so competitors can properly manage stress and peak performance in adverse scenarios.

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

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