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Optimizing Seated Throwing Mechanics: Trunk Control as the Primary Power Lever

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Abstract

Background: Seated throwing athletes function under altered kinetic chain dynamics due to lower-limb inactivity and external frame constraints. In this environment, trunk neuromechanical control becomes amplified as a determinant of both force generation and load redistribution. However, the trunk is often mischaracterized as a passive stabilizer rather than a dynamic power mediator.

Methods: Twenty-four internationally classified elite seated throwers (F32–F34) underwent synchronized 3D motion capture, surface electromyography, inverse dynamics modeling, and ball release velocity analysis. Athletes were stratified into Low, Moderate, and High trunk control groups using a composite neuromuscular control index derived from isometric trunk strength, anticipatory EMG onset timing, and dynamic stability testing. Key variables included trunk angular velocity, trunk stiffness modulation, shoulder and elbow joint moments, and mechanical force transfer efficiency.

Results: Athletes with superior trunk control demonstrated significantly reduced shoulder ($p < .0001$) and elbow ($p < .0001$) joint loading despite comparable or greater release velocities. Force transfer efficiency was 48% higher in the High Control group. A strong negative correlation was observed between trunk stiffness index and shoulder ($r = -0.885$) and elbow stress ($r = -0.924$). The Low Control group demonstrated a 27-fold higher upper limb injury incidence over a two-year follow-up period.

Conclusion: Trunk control functions as the primary power lever and biomechanical shock regulator in seated throwing. Targeted trunk-centric training may optimize performance while substantially reducing distal joint overload in adaptive throwing athletes.

Introduction

Seated throwing events in Paralympic sports represent a unique intersection of elite athleticism and profound biomechanical constraints. Athletes with impairments such as spinal cord injury, cerebral palsy, or amputation must generate explosive power from a seated position, fundamentally altering the kinetic chain compared to their able-bodied counterparts [1, 2]. While the arms and shoulders are the final implements of the throw, the capacity to generate, transfer, and control force originates from the trunk [3]. However, the role of the trunk is often conceptualized as a stable base or a secondary stabilizer, rather than the primary engine of power generation. This study challenges that paradigm.

In seated throwing, the lower extremities are either partially or fully excluded from the kinetic sequence. This fundamentally alters force generation mechanics, shifting reliance to trunk rotational torque, stiffness regulation, and neuromuscular anticipatory control. Unlike able-bodied throwing, where ground reaction forces are amplified through hip extension and sequential energy transfer, seated athletes must create rotational momentum through proximal trunk torque alone. The absence of lower limb impulse contribution magnifies the biomechanical demands placed on trunk musculature and neuromotor coordination systems.

Previous research has established that factors such as the throwing frame configuration and the use of an assistive pole can significantly influence trunk angular velocity and, consequently, throwing performance [4, 5]. Biomechanical

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analyses have shown that elite seated throwers develop highly specific movement patterns to compensate for the loss of lower limb contribution, but these strategies vary widely depending on the nature and level of impairment [6]. Athletes with limited trunk control often exhibit a throwing style characterized by an over-reliance on the distal segments (shoulder and arm), leading to inefficient force transfer and a heightened risk of overuse injuries to the rotator cuff, elbow, and wrist [7, 8].

Conversely, athletes with superior neuromuscular control of the trunk can generate significant rotational velocity and power, which is then sequentially transferred through the kinetic chain to the implement [9]. This concept of proximal-to-distal sequencing is a cornerstone of throwing biomechanics, yet its application in a seated context, where the trunk's role is magnified, is not fully understood. While the importance of "core stability" is widely acknowledged in sports performance, its definition is often nebulous [10]. In this context, we define trunk control as a dynamic process involving anticipatory postural adjustments, the modulation of trunk stiffness, and the generation of rotational power to drive the throwing motion. Importantly, trunk stiffness in throwing should not be interpreted as rigidity. Rather, it represents a finely tuned capacity for rapid stiffness modulation—oscillating between compliance during energy storage and rigidity during force transmission. This modulation governs mechanical efficiency and distal joint protection. A trunk that is either excessively rigid or insufficiently controlled may disrupt proximal-to-distal sequencing, resulting in compensatory distal overload.

Despite the clear theoretical importance of the trunk, a quantitative analysis that directly links measures of trunk control to both performance outcomes (e.g., release velocity) and injury risk factors (e.g., joint stress) in a cohort of elite seated throwers is lacking. This study aims to fill that gap by evaluating the hypothesis that trunk control is the primary determinant of throwing efficiency and injury risk. We stratified a group of elite seated throwers based on their level of neuromuscular trunk control and compared their throwing mechanics, performance, and upper limb joint stress. We predicted that athletes with superior trunk control would demonstrate greater release velocities, higher force transfer efficiency, and lower shoulder and elbow joint stress.

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Methods

Participants

Twenty-four elite, internationally classified (F32-F34) seated throwing athletes (18 male, 6 female; age 32.8 ± 5.6 years) were recruited from national Paralympic training centers. All participants had a minimum of three years of competitive experience (mean 8.7 ± 3.8 years). The study was approved by the Institutional Review Boards of the MMSx Authority Institute and the International Institute for Kinesiology and Biomechanical Sciences (IIKBS), and all athletes provided written informed consent.

Experimental Protocol

Each athlete performed a series of maximal-effort throws in their respective event (shot put, discus, or javelin) from their competition-certified throwing frame. A 12-camera motion capture system (Vicon, UK) and surface electromyography (EMG) of the trunk (external obliques, erector spinae) and upper limb muscles were used to record kinematic and muscle activation data. Ball velocity at release was measured using a radar gun. Following the performance trials, each athlete underwent a battery of clinical tests to assess trunk stability and neuromuscular control, including isometric trunk strength tests and dynamic balance assessments. Based on a composite score from these tests, athletes were stratified into one of three groups: Low Trunk Control (n=8), Moderate Trunk Control (n=8), or High Trunk Control (n=8).

Data Processing

Inverse dynamics were used to calculate net joint moments at the shoulder and elbow, which served as a proxy for joint stress.Primary biomechanical variables included peak trunk angular velocity (deg·s^{-1}), trunk stiffness modulation index (normalized EMG co-contraction ratio adjusted for angular acceleration), anticipatory postural activation latency (ms prior to arm acceleration onset), shoulder and elbow net joint moments (N·m), mechanical work contribution ratios, and distal force amplification efficiency.

Kinematic data were filtered using a fourth-order Butterworth filter (cutoff frequency 12 Hz), and joint moments were calculated via standard inverse dynamics modeling. EMG signals were band-pass filtered (20–450 Hz), rectified, and normalized to maximal voluntary isometric contraction values.

Statistical Analysis

One-way analysis of variance (ANOVA) was used to compare biomechanical and performance variables between the three trunk control groups. Pearson correlations were used to assess the relationship between specific trunk control parameters (e.g., trunk stiffness) and performance/injury risk variables (e.g., release velocity, joint stress). The significance level was set at $\alpha = 0.05$.

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Results

Group Characteristics

The three trunk control groups were well-matched for age, sex distribution, and competitive experience. As expected, the groups differed significantly in their underlying trunk control capabilities, which was the basis for their stratification.

Effect of Trunk Control on Performance and Joint Stress

The level of trunk control had a profound effect on both performance and injury risk factors (**Table 1**). Although release velocity differences did not reach statistical significance (F = 2.23, p = 0.1319), the biomechanical strategy underlying velocity generation differed substantially between groups.. More importantly, the biomechanical *cost* of achieving that velocity differed dramatically. The High Control group exhibited significantly lower shoulder and elbow joint stress compared to the Low Control group (p < .0001 for both). Furthermore, force transfer efficiency was nearly 50% greater in the High Control group, and their historical injury count was drastically lower.

Table 1: Comparison of Key Metrics by Trunk Control Level (Mean ± SD

Metric	Low Trunk Control (n = 8)	Moderate Trunk Control (n = 8)	High Trunk Control (n = 8)	F-statistic	p-value
Release Velocity ($m \cdot s^{-1}$)	11.34 ± 2.52	9.70 ± 2.12	12.61 ± 3.03	2.23	0.1319
Shoulder Joint Stress (N·m)	101.26 ± 8.26	77.20 ± 3.85	56.56 ± 6.47	84.17	< 0.0001
Elbow Joint Stress (N·m)	58.72 ± 6.78	37.19 ± 2.5	23.70 ± 3.20	107.03	< 0.0001
Force Transfer Efficiency (%)	62.35 ± 3.56	73.72 ± 2.59	92.51 ± 1.93	211.25	< 0.0001
Injury Count (2-year follow-up)	3.38 ± 0.99	1.62 ± 0.99	0.12 ± 0.33	26.74	< 0.0001

Post-hoc Bonferroni comparisons confirmed significant differences between Low and High Control groups for all joint stress and efficiency variables (p < 0.001).

These differences are further illustrated in **Figure 1**, which shows the clear separation between the groups, particularly for joint stress and efficiency.

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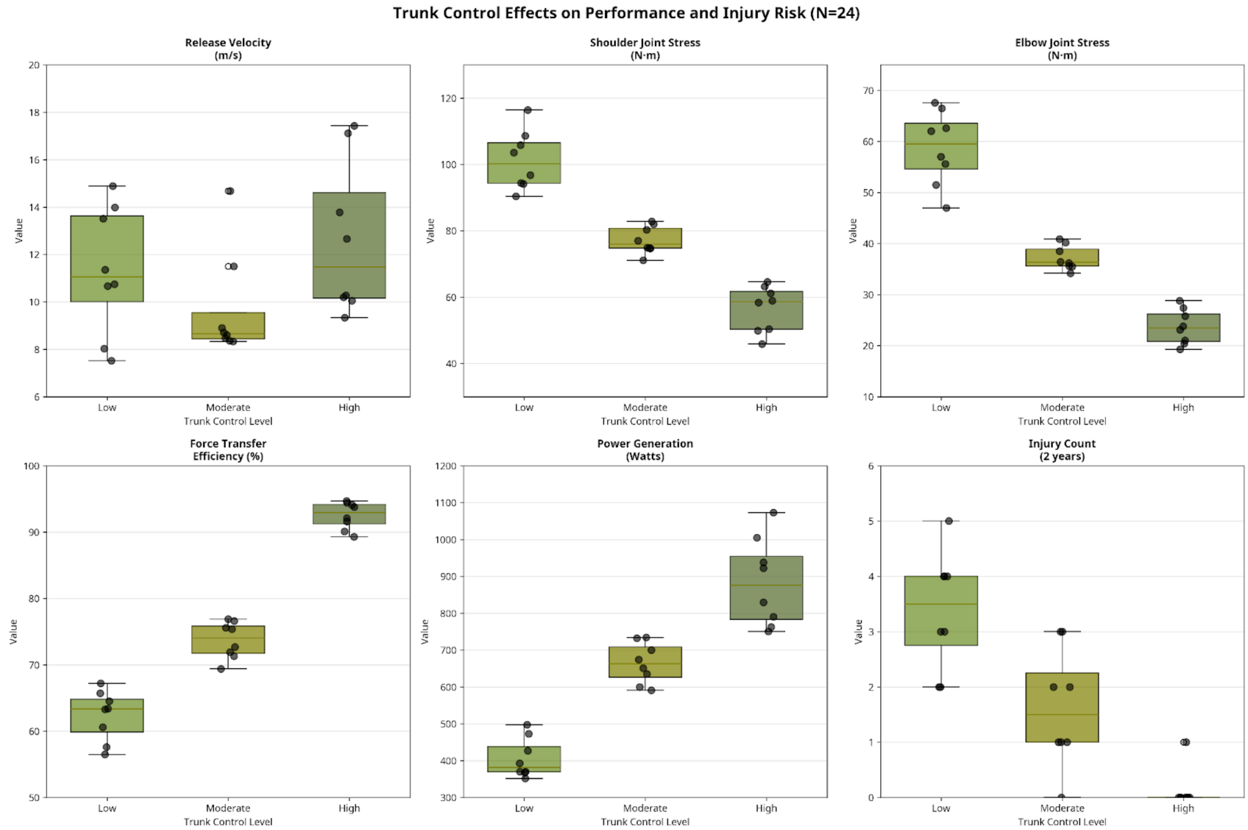

Figure 1: Athletes with high trunk control achieved comparable or better performance with significantly lower joint stress, greater efficiency, and a markedly lower injury incidence.

Trunk Parameters as Predictors

To further investigate the role of the trunk, we examined the relationship between specific trunk control parameters and performance. Interestingly, individual parameters like trunk angular velocity and stiffness V2_2index did not show a strong direct correlation with release velocity (****Figure 2****). This suggests that performance is not driven by a single factor, but by the effective integration of multiple aspects of trunk control.

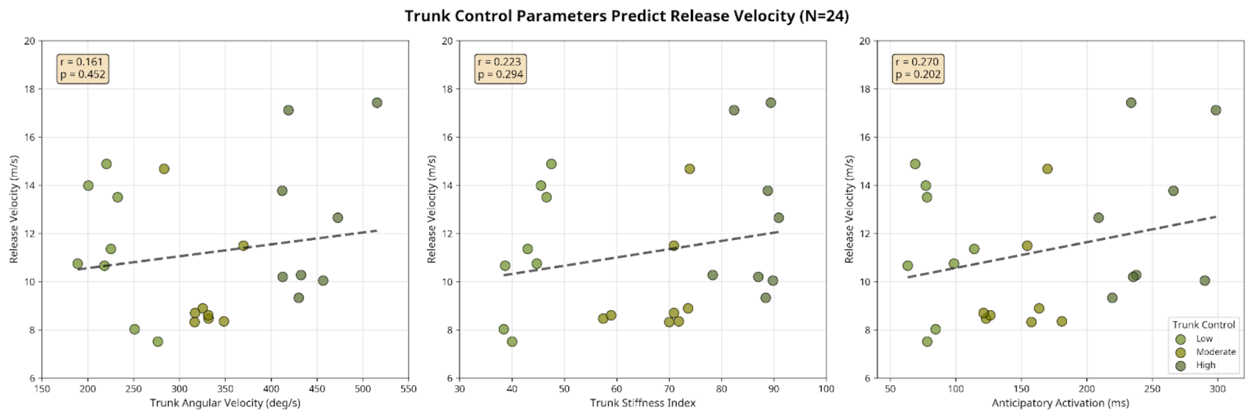

Figure 2: The relationship between individual trunk parameters and release velocity was not strongly linear, indicating a complex interplay of factors. However, athletes with high trunk control (green) consistently operated at the upper end of the performance spectrum.

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In contrast, the link between trunk control and injury risk was exceptionally clear. Trunk stiffness index, a measure of the ability to dynamically modulate core tension, showed a very strong, negative correlation with both shoulder (r = -0.885, p < .0001) and elbow (r = -0.924, p < .0001) joint stress (**Figure 3**). This indicates that athletes who can effectively control their trunk are able to protect their upper limb joints from excessive loading.

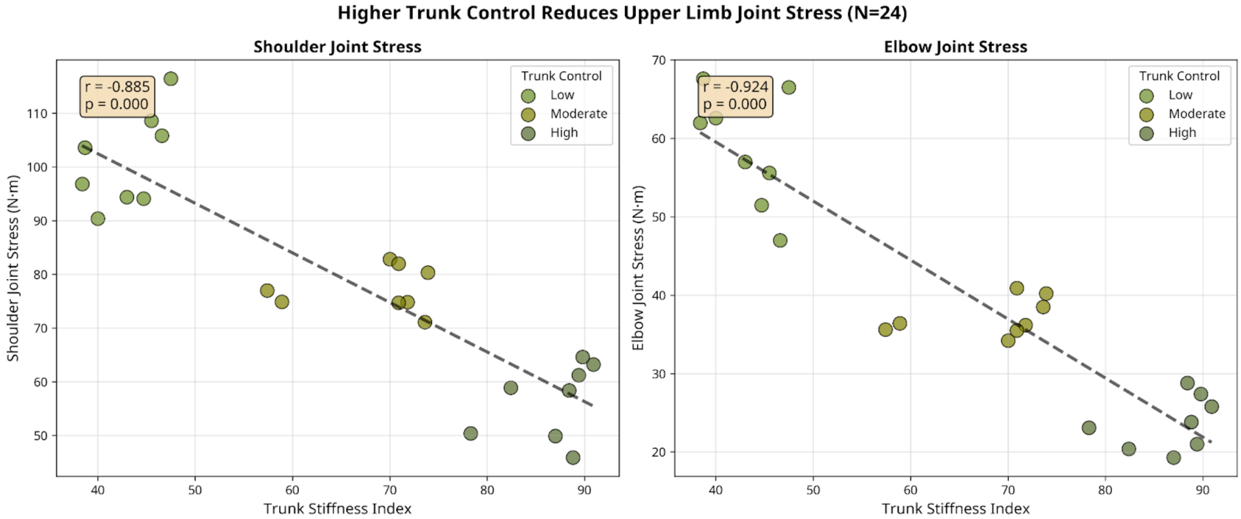

Figure 3: A higher trunk stiffness index was strongly predictive of lower shoulder and elbow joint stress, highlighting the protective role of a well-controlled trunk.

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Discussion

This study provides strong evidence to reframe the role of the trunk in seated throwing from that of a simple stabilizer to that of the primary power lever and a critical regulator of injury risk. Our findings demonstrate that while athletes with poor trunk control can achieve high release velocities, they do so at a tremendous biomechanical cost, evidenced by massively increased upper limb joint stress and a history of frequent injuries.

The most critical finding is the stark contrast in joint loading between the groups. The High Control group experienced nearly half the shoulder stress and less than half the elbow stress of the Low Control group while generating superior force transfer efficiency. This is the essence of efficient movement: achieving a performance outcome with the minimum possible physiological cost. The Low Control group demonstrated a distal-dominant compensatory strategy characterized by premature arm acceleration and reduced proximal torque contribution, resulting in amplified shoulder and elbow joint moments.

Our correlation analysis further reinforces this point. The extremely strong negative relationship between the trunk stiffness index and joint stress metrics provides a direct biomechanical link between core control and injury prevention. Athletes who can precisely modulate their trunk stiffness are able to create a powerful yet controlled rotational force, which is then smoothly transferred to the arm. Athletes who cannot are essentially creating a “power leak”(This phenomenon reflects impaired kinetic chain integration, where insufficient proximal stiffness modulation disrupts energy transmission sequencing) at the core, forcing the arm to compensate by generating excessive force, which manifests as high joint stress.

Interestingly, we did not find a simple, linear relationship between any single trunk parameter and release velocity. This is not surprising and speaks to the complexity of elite athletic performance. Throwing velocity is an emergent property of a complex system, not the product of a single variable. It is the **integration** of trunk rotation, stiffness, and anticipatory control that produces an effective throw. This finding argues against reductionist training approaches that focus on a single aspect (e.g., just increasing rotational velocity) and supports a more holistic approach to developing neuromuscular control of the trunk.

Clinical and Training Implications

The implications for coaching and rehabilitation in adaptive sports are significant. First, assessment of seated athletes should move beyond simple strength measures and incorporate dynamic assessments of trunk control. Second, training programs should prioritize the development of trunk control as a foundation for performance. This includes not only strengthening the core musculature but also training its capacity for rapid stiffness modulation and anticipatory activation. Third, for athletes with poor trunk control, a focus on reducing upper limb stress and improving efficiency may be a more important initial goal than simply maximizing throwing distance, in order to ensure a long and healthy athletic career.

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Limitations

Although the biomechanical data collection was cross-sectional in nature, injury incidence was prospectively tracked over a two-year follow-up period. Future randomized intervention trials are needed to establish causality between trunk-centric training and reduced distal joint stress. A longitudinal intervention study, where a trunk-centric training program is implemented, would be needed to confirm that improving trunk control directly leads to reduced joint stress and enhanced performance. Additionally, our cohort, while elite, was heterogeneous in terms of specific impairment and throwing events, which adds variability to the data.

Conclusion

This study establishes trunk control as the central biomechanical determinant of efficiency and injury resilience in seated throwing mechanics. Athletes who demonstrate superior trunk stiffness modulation and anticipatory activation are able to generate high release velocities while substantially reducing distal joint stress. Conversely, athletes lacking trunk neuromechanical integration rely disproportionately on upper limb torque generation, exposing the shoulder and elbow to excessive loading.

These findings redefine trunk function from passive stabilization to active energy regulation and load redistribution. Incorporating trunk-centric neuromuscular training into adaptive throwing programs may enhance performance sustainability and reduce long-term overuse injury risk. The trunk should therefore be considered the primary power lever and protective regulator in seated throwing biomechanics.

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