Modeling stability in gymnastics: mediation and moderation of arm and abdominal effects on handstand performance

Modelado de la estabilidad en gimnasia: mediación y moderación de los efectos de los brazos y el abdomen en el rendimiento del pino

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Abstract

Introduction: Handstand performance in gymnastics varies across apparatuses, with antero-posterior stability playing a key role in maintaining balance.
Objectives: This study explores the biomechanical interplay between abdominal, arm, and floor handstand torso stability in gymnastics, towards the torso stability of handstand performance on parallel bars.
Methods: Twenty-five participants completed four tasks: holding a 10-kg dumbbell for 15 seconds (arm stability), maintaining a floor forearm plank for 15 seconds (abdominal stability), and performing 10-second of steady handstands on both the floor and parallel bars. Inclinometer sensors recorded sagittal-axis movement to quantify stability. Statistical analysis steps included correlation, normality testing, linear regression, bootstrapped mediation and moderation models, and path visualization.
Results: Regression analysis revealed significant direct effects of abdominal and arm stability on torso stability during handstands on P-bars. Mediation analysis showed that floor torso stability significantly mediated the effect of arm stability, but not abdominal stability. Moderation analysis confirmed that floor torso stability amplified the influence of arm control, while no such interaction was found for abdominal control.
Discussion: Bootstrapping validated the robustness of direct and moderated effects. The analysis revealed a range of meaningful and intriguing mediation and moderation pathways among the studied variables, highlighting the complexity of their interrelationships.
Conclusion: Despite the small sample size, the study provides a theoretically grounded framework for future research in gymnastics biomechanics and wearable sensor applications.

Keywords

Biomechanics; gymnastics; inclinometer sensors; human stability; modelling analysis.

Resumen

Introducción: El rendimiento en la parada de manos en gimnasia varía según el aparato, siendo la estabilidad antero-posterior un factor clave para mantener el equilibrio.
Objetivos: Este estudio explora la interacción biomecánica entre la estabilidad abdominal, de los brazos y del torso durante la parada de manos en el suelo, en relación con el rendimiento de la estabilidad del torso sobre las barras paralelas.
Métodos: Veinticinco participantes realizaron cuatro tareas: sostener una mancuerna de 10 kg durante 15 segundos (estabilidad del brazo), mantener una plancha sobre los antebrazos durante 15 segundos (estabilidad abdominal), y ejecutar paradas de manos estables de 10 segundos tanto en el suelo como en las barras paralelas. Se utilizaron sensores de inclinómetro para registrar el movimiento en el eje sagital y cuantificar la estabilidad. El análisis estadístico incluyó pruebas de correlación, normalidad, regresión lineal, modelos de mediación y moderación con bootstrapping, y visualización de rutas.
Resultados: El análisis de regresión reveló efectos directos significativos de la estabilidad abdominal y del brazo sobre la estabilidad del torso durante las paradas de manos en las barras paralelas. El análisis de mediación mostró que la estabilidad del torso en el suelo medió significativamente el efecto de la estabilidad del brazo, pero no el de la estabilidad abdominal. El análisis de moderación confirmó que la estabilidad del torso en el suelo amplificó la influencia del control del brazo, mientras que no se observó tal interacción en el caso del control abdominal.
Discusión: El método de bootstrapping validó la solidez de los efectos directos y moderados. El análisis reveló una variedad de rutas de mediación y moderación significativas e interesantes entre las variables estudiadas, lo que pone de manifiesto la complejidad de sus interrelaciones.
Conclusión: A pesar del tamaño reducido de la muestra, el estudio proporciona un marco teórico sólido para futuras investigaciones en biomecánica gimnástica y aplicaciones de sensores portátiles

Palabras clave

Análisis de Modelado; biomecánica; estabilidad humana: gimnasia; sensores de inclinómetro.

Introduction

The handstand is a cornerstone skill in artistic gymnastics, emblematic of advanced athletic proficiency. It demands a high degree of neuromuscular coordination, postural control, and muscular strength across multiple body segments. Whether performed on the floor or on apparatuses such as parallel bars and still rings, the ability to maintain a stable handstand reflects the gymnast's capacity to manage complex biomechanical interactions—particularly between upper limb strength and core stability. Despite its prominence in gymnastics routines, the biomechanical and physiological foundations of handstand control remain underexplored, especially in relation to the varying mechanical demands posed by different apparatuses. Research has shown that handstand proficiency significantly influences athletic development across skill levels, from novice gymnasts to elite international competitors (Kochanowicz & Kochanowicz, 2015). Defined as an inverted vertical posture supported by one or both hands, the handstand is universally recognized as a fundamental balance element in artistic gymnastics (Yudho et al., 2022), and its importance is consistent regardless of performance level (Rohleder & Vogt, 2018b). Psychological factors appear to play a limited role in postural stability during natural standing positions. However, in the handstand position, elevated physical and cognitive anxiety and reduced self-confidence have been linked to diminished stability, but in contrast, general self-efficacy and motivational orientation do not exert a direct influence on postural control (Omorczyk et al., 2019). Stabilometric analyses further reveal that experienced gymnasts demonstrate superior postural control during handstands (Sobera et al., 2019), and that variations in handgrip technique can alter muscle activation patterns, engaging not only the forearm but also distal muscles such as the rectus femoris and deltoids (Kochanowicz et al., 2019).

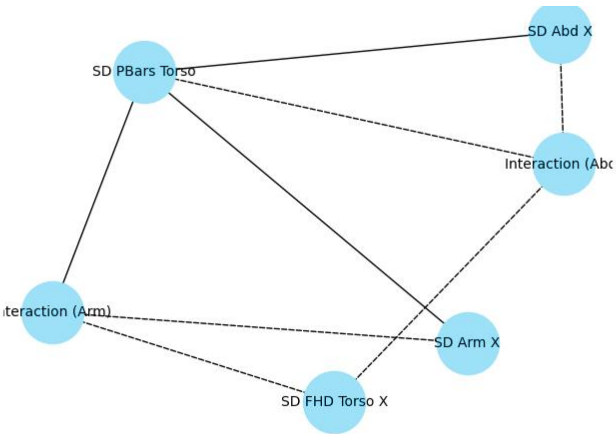
In older adults, the absence of visual input during both free standing and handstand positions leads to deterioration in stability indices, especially in the anteroposterior direction, in the other hand, Interestingly, mediolateral stability remains unaffected, suggesting that seniors engaged in artistic gymnastics maintain effective control of center of pressure movement in the frontal plane without reliance on visual cues (Puszczałowska-Lizis & Omorczyk, 2019). Body posture and hip flexion have also been identified as critical determinants of handstand performance (Kojima et al., 2021). These findings support the hypothesis that core and arm stability contribute differentially to handstand control depending on the apparatus. Floor-based handstands typically require heightened upper limb proprioception and shoulder girdle strength to counteract gravitational forces and maintain vertical alignment. In contrast, handstands on parallel bars demand greater core engagement to stabilize the torso and manage the elevated center of mass. Recent developments in wearable sensor technology—particularly inclinometer-based systems—have enhanced the precision and mobility of postural stability assessments. These sensors offer real-time data on tilt and motion, making them valuable tools for evaluating limb and core stability during dynamic movements (Yudho, Hasanuddin, et al., 2024), simpler, faster (Cejudo et al., 2020), and affordable to use (Barrett et al., 2018). It also has a good reliability in measuring joint position sense and to measure force reproduction (Dover & Powers, 2003).

The primary objective of this study is to investigate the biomechanical relationships between abdominal, arm, and torso stability during handstand performance in artistic gymnastics, with a particular focus on execution on parallel bars. By leveraging inclinometer sensor technology, the research aims to quantify sagittal-axis movement and assess how core and limb control contribute to overall postural alignment. The study also seeks to determine the direct, mediating, and moderating effects (Zitzmann & Helm, 2021), of abdominal and arm stability on torso control, thereby providing a deeper understanding of the kinetic chain involved in handstand execution, with a relative small number of samples. Ultimately, the goal is to develop a sensor-based quantitative analytical framework that enhances technique optimization and informs future research in gymnastics biomechanics.

Method

This study employed a multi-step statistical framework to investigate the predictive relationships between two exogenous variables—arm stability and abdominal (core) stability—and two outcomes: handstand torso stability on the floor and on parallel bars. Twenty-five participants completed four tasks: holding a 10-kg of urethane DURA-BELL Dumbbell with both hands for 15 seconds (to assess arm stability) towards the 90 degrees horizontally in sagittal axis, maintaining a floor forearm plank for 15 seconds (to assess abdominal stability), and performing 10-second handstands on both the floor and parallel bars. Wit-Motion® BLE901CL5.0 wireless inclinometer sensor, which was strapped to the participants' mid-sternum area with an adjustable elastic harness to ensure consistent placement. The sensor, capable of recording at 10 Hz, transmitted angular displacement data via Bluetooth to a connected laptop, recorded sagittal-axis movement to quantify stability across all tasks. Given the small sample size and non-normal distribution of the data (confirmed via Shapiro-Wilk tests), non-parametric and bootstrapped methods were prioritized. Spearman correlation was used to explore monotonic relationships among variables. Multiple linear regression was applied to test direct effects, while bootstrapped mediation and moderation models were used to examine indirect and interaction effects. A path diagram was constructed to visualize the relationships among variables, distinguishing statistically significant pathways from exploratory ones.

Figure 1. Path Diagram



The diagram presents a visual representation of the relationships among key variables involved in handstand stability analysis. Statistically significant pathways, confirmed through regression and bootstrapping techniques, are illustrated with solid arrows, while gray dashed arrows denote exploratory or non-significant connections. Each node in the diagram corresponds to a specific stability metric: abdominal stability, arm stability, torso stability during floor handstands, and torso stability during handstands on parallel bars. Additionally, an interaction node captures a moderate effect between arm stability and floor torso control. This integrated visualization highlights both direct and indirect relationships, emphasizing the statistically validated pathways while also acknowledging areas that warrant further investigation.

Participants

Descriptive statistics were obtained for the performance and demographic variables across a sample of 25 participants as well for the demographic variables, including age, weight, height, and body mass index (BMI), based on a sample of 25 participants. The mean age was 21 years (SD = 4.94), with values ranging from 17 to 31. Participants had an average weight of 58.3 kg (SD = 5.47) and an average height of 166 cm (SD = 4.56), resulting in a mean BMI of 21.1 (SD = 1.67).

Procedure

To evaluate postural stability across various body segments, wireless inclinometer sensors were securely attached to specific anatomical landmarks according to each test protocol. These sensors operated at a frequency of 10 Hz, capturing 10 data points per second. For each movement trial, the standard deviation (SD) of the recorded angular data was calculated to represent the degree of motion variability, with each trial consisting of approximately 100 data points. The measured stability pertains specifically to motion along the sagittal (X) axis, corresponding to the antero-posterior direction. The inclinometer records and its measurement's validity usage regarded to the previous source (Yudho, Fachrezzy, et al., 2024) in measuring postural stability of Aerobic gymnasts, (Yudho et al., 2025) in measuring effect of physical activity towards postural stability in university students, and (Romero-Franco et al., 2016) in a similar usage of instrument that assessing the knee joint position. Arm stability was measured by strapping the sensor onto the dorsal side of the wrist. Participants were instructed to hold a 10 kg dumbbell with both hands extended at 90 degrees in the sagittal plane and remain still for 15-s as shown in the figure 2 below.

Figure 2. Dumbbell holding test

Abdominal stability during forearm plank exercise was measured by placing the sensor on the sternum area with an adjustable rubber strap while participants held a forearm plank position for 15-s as shown in figure 3 below.

Figure 3. Forearm plank Position Recording

Torso stability during a floor handstand was evaluated by placing the sensor on the sternum while participants maintained a static handstand position on a floor mat for 10-s. For torso stability during a handstand on parallel bars, the same protocol was followed, with the only difference being the elevated support surface instead of the floor.

Figure 4. Floor and P-Bars handstand stability recording

Each measurement began with a zero-point calibration to ensure that all deviations recorded during the test represented postural instability relative to a standardized axis. The table presents Standard Deviation (SD) scores used to interpret the sample's stability performance, calculated from 100–150 data recordings per measurement, each lasting 10–15 seconds. These scores represent variability in motion along the antero-posterior axis, as part of the experimental procedures conducted in this study.

Table 1. Data descriptives in degree of motion (°)

Statsistics	SD Arm-X (°)	SD FHD-X (°)	SD P-Bars-X (°)	SD Abd-X (°)
N	25	25	25	25
Mean	7.72	7.47	7.2	5.91
Median	8.18	7.02	4.16	3.28
SD	3.48	5.53	5.75	6.63
Min	0.53	0.45	0.59	0.1
Max	12.8	17.1	18	21.8
S-Wilk W	0.84	0.91	0.84	0.8
S-Wilk p	0	0.03	0	<.001

The descriptive analysis of the study variables reveals meaningful variation in physical stability and demographic characteristics among the participants. Arm stability shows a mean score of 7.72° with a standard deviation of 3.48, indicating moderate variability in upper limb strength across individuals. Torso stability during floor handstands and parallel bars handstands exhibit slightly lower mean values of 7.47° and 7.20 °, respectively, but with higher standard deviations (5.53 and 5.75), suggesting greater dispersion in torso control performance. Notably, abdominal stability, assessed via a 15-s forearm plank, has the lowest mean score of 5.91 and the highest variability (SD = 6.63).

Data analysis

To analyze the influence of handstand gymnastics ability, we began by assessing the normality of each variable's distribution using the Shapiro-Wilk test, which is well-suited for small to moderate sample sizes and highly sensitive to deviations from normality. Next, we employed the Spearman correlation test to examine the strength and direction of monotonic relationships among variables related to handstand stability, including abdominal stability, arm stability, torso stability during handstands on the floor, and torso stability on parallel bars. To investigate the direct effects of abdominal and arm stability on torso stability during handstands on parallel bars, we fitted a multiple linear regression model. We then conducted bootstrapped mediation analyses to determine whether torso stability on the floor mediated the effects of abdominal and arm stability on parallel bar performance. Additionally, we tested for moderation by constructing a linear regression model with an interaction term to assess whether torso stability on the floor moderated the relationship between abdominal stability and torso stability on parallel bars. Lastly, to ensure the reliability of our statistical findings across regression and moderation models, we applied bootstrapping with 1,000 resamples to generate robust confidence intervals for each model coefficient.

Results

In the context of analyzing the influence of handstand gymnastics ability, a preliminary step involved assessing the normality of the data distributions for each variable using the Shapiro-Wilk test. This test is particularly sensitive to deviations from normality and is suitable for small to moderate sample sizes.

The results revealed that none of the variables met the criteria for normal distribution. Specifically, the p- value results of normality for abdominal stability (SD Abd X) p = .799, arm stability (SD Arm X) p = .001, torso stability on the floor (SD FHD Torso X) p = .026, and torso stability on P-bars (SD P-Bars Torso X) p = .001 almost all yielded p-values below the conventional threshold of .05, indicating statistically significant departures from normality. These findings suggest that the data are lack of normality and may warrant the use of non-parametric or robust statistical techniques.

The next step to describe the correlation matrix we used Spearman correlation test to provide insight into the strength and direction of monotonic relationships among the variables related to handstand gymnastics stability. In this analysis, the variables included abdominal stability, arm stability, torso stability during handstand on the floor, and torso stability during handstand on parallel bars. The correlation matrix reveals an exceptionally high degree of synchronization among arm stability, floor handstand stability, bars handstand stability, and abdominal stability, with all inter-variable correlations exceeding .9996. This indicates that fluctuations in one area are almost perfectly mirrored by the others, suggesting a tightly integrated motor control system. Notably, the slightly lower correlation involving bars handstand stability (.9994) may reflect subtle apparatus-specific demands, but overall, the data points to a highly coordinated and stable performance across upper body and core segments.

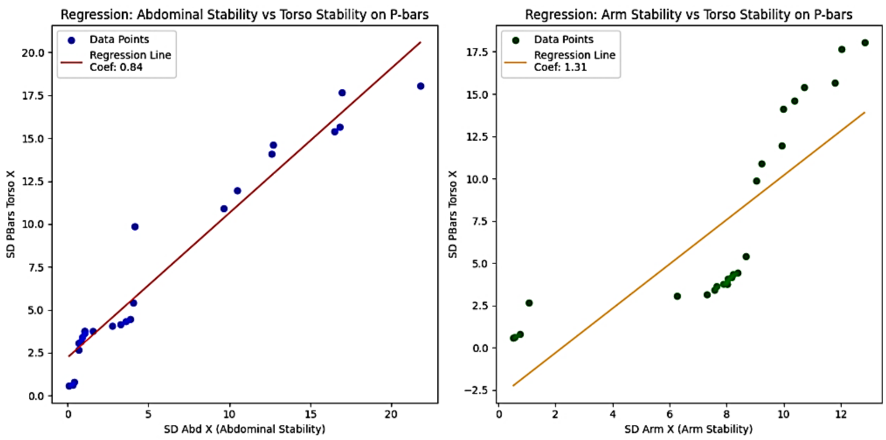
To explore the direct influence of abdominal stability and arm stability on torso stability during handstand on P-bars (SD P-Bars Torso X), a multiple linear regression model was fitted. The model yielded a high R^2 value of .957, indicating that 95.7% of the variance in torso stability on P-bars is explained by the two predictors. This suggests a strong overall model fit. Result of the SD Abd X (Abdominal Stability) showed a highly significant positive effect on the outcome, with a coefficient of .730 and a p-value < .001. This means that increases in abdominal stability are strongly associated with improved torso stability on P-bars. The SD Arm X (Arm Stability) also had a statistically significant positive effect, with a coefficient of .291 and a p-value of .013, indicating a meaningful contribution, though less dominant than abdominal stability.

Table 2. Regression Coefficients

Predictor	Coefficient	Std. Error	t-value	p-value	95% CI
Intercept	.639	.675	.948	.354	[-.760, 2.039]
SD Abd X	.730	.057	12.924	<.001	[.613, .848]
SD Arm X	.291	.107	2.706	.013	[.068, .514]

The intercept was not statistically significant, which is common in models where predictors explain most of the variance. The residual diagnostics (Omnibus and Jarque-Bera tests) suggest some skewness and kurtosis, which aligns with earlier findings of non-normality in the data. This regression confirms that both abdominal and arm stability are directly and positively associated with torso stability during handstand on P-bars, with abdominal stability being the stronger predictor.

Figure 5. Comparison of regression analysis plot of abdominal and arm stability towards P-Bars stability



To examine whether torso stability during handstand on the floor serves as a mediating variable, we conducted bootstrapped mediation analyses on two predictive pathways: one originating from abdominal stability and the other from arm stability, both targeting the outcome of torso stability on parallel bars.

Table 3. Mediation effects

Path	Indirect Effect	95% CI	p-value
SD Abd X → SD FHD Torso X → SD P-Bars Torso X	.202	[-.034, .471]	.096
SD Arm X → SD FHD Torso X → SD P-Bars Torso X	1.219	[.794, 1.702]	0

The first mediation model, assessing the indirect effect of abdominal stability through floor torso stability, yielded an effect size of .2024 with a 95% confidence interval ranging from −.0339 to .4707 and a p-value of .096. Although this result was not statistically significant at the conventional .05 threshold, it suggested a potential trend worth exploring in future studies. In contrast, the second model revealed a statistically significant mediation effect of floor torso stability in the relationship between arm stability and P-bars torso stability. The indirect effect was 1.2188, with a 95% confidence interval of .7941 to 1.7018 and a p-value of <.001. This finding supports the hypothesis that arm control influences torso alignment during handstands on the floor, which in turn enhances stability on the parallel bars. These results highlight the functional role of torso control as a biomechanical bridge, particularly in the transfer of upper limb control to apparatus-based performance.

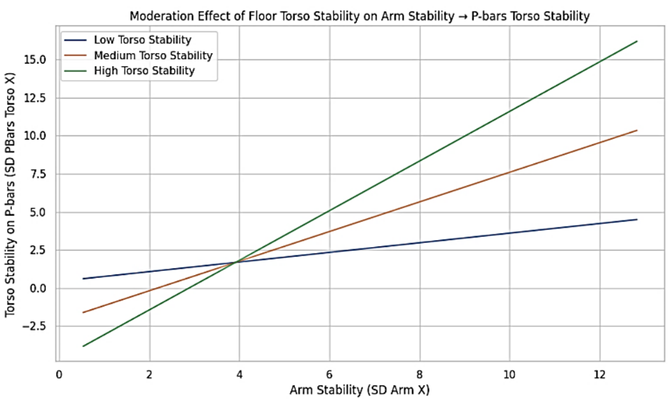
Table 4. Moderation of arm and abdominal to floor handstand torso stabilities

Predictor	Coefficient	p-value
Intercept	.44	
SD Arm X	-.19	.605
SD FHD Torso X	-.23	.158
Interaction (Arm ✻ Torso)	.119	<.001
Intercept	.56	
SD Abd X	1.049	.02
SD FHD Torso X	.197	.182
Interaction (Abd ✻ Torso)	-.023	.312

The interaction term (SD Arm X ✻ SD FHD Torso X) was statistically significant (coefficient = .1186, p < .001), suggesting that the effect of arm stability on P-bars performance is contingent on the level of torso stability during floor handstands. Specifically, as floor torso stability increases, the influence of arm control becomes more pronounced. Interestingly, the main effects of SD Arm X (p = .605) and SD FHD Torso X (p = .158) were not significant, indicating that the interaction—not the individual predictors—was the key driver of the outcome. This finding was further supported by a simple slope visualization, which illustrated that the relationship between arm stability and P-bars torso stability steepens across low, medium, and high levels of floor torso stability.

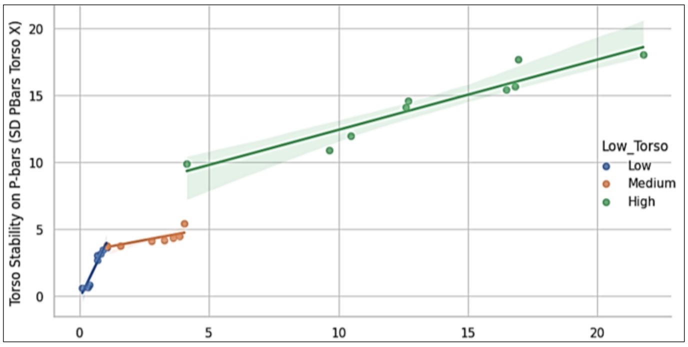
To determine whether torso stability during handstand on the floor moderates the relationship between abdominal stability and torso stability on parallel bars, a linear regression model was constructed with an interaction term.

Figure 6. Simple slopes of the arm moderation effect



The model demonstrated a strong overall fit, with an R^2 of .957, indicating that 95.7% of the variance in P-bars torso stability was explained. The main effect of abdominal stability was statistically significant (coefficient = 1.048, p = .020), confirming its direct and substantial contribution to torso control on the apparatus. However, the main effect of floor torso stability was not significant (p = .182), and more importantly, the interaction term (SD Abd X ✻ SD FHD Torso X) was also not statistically significant (coefficient = –.0225, p = .312). Simple slopes visualization further supported this conclusion, showing relatively parallel regression lines across low, medium, and high levels of floor torso stability. These findings indicate that while abdominal stability plays a critical direct role in maintaining torso alignment during handstands on P-bars, its effect is consistent regardless of torso control on the floor, and not subject to moderation.

Figure 7. Simple slopes of the abdominal moderation effect



To ensure the reliability of the statistical findings across regression and moderation models, bootstrapping was employed as a validation technique. This method involved resampling the dataset 1,000 times to generate robust confidence intervals for each model coefficient.

Table 5. Boostrapped Confidence Interval

Model	Predictor	95% CI	p-value
Main Effects	Intercept	[-.10, 1.69]	.263
Main Effects	SD Abd X	[.63, .86]	< .001
Main Effects	SD Arm X	[.12, .46]	< .001
Moderation (Arm)	Intercept	[.44, 3.34]	< .001
Moderation (Arm)	SD Arm X	[-.19, .26]	.245
Moderation (Arm)	SD FHD Torso X	[-2.23, .30]	.238
Moderation (Arm)	Interaction	[.06, .30]	< .001
Moderation (Abd)	Intercept	[.56, 2.21]	< .001
Moderation (Abd)	SD Abd X	[-.14, 1.91]	.282
Moderation (Abd)	SD FHD Torso X	[-.17, .62]	.297
Moderation (Abd)	Interaction	[-.06, .04]	.051

In the main effects model, both abdominal stability and arm stability showed statistically significant confidence intervals that did not include zero, confirming their direct influence on torso stability during handstands on parallel bars. In the moderation model involving arm stability, the interaction term (SD Arm X ✻ SD FHD Torso X) was also validated as significant, reinforcing the conclusion that floor torso stability amplifies the effect of arm control. These bootstrapped results strengthen the credibility of the significant pathways identified in the study and help distinguish robust effects from exploratory ones, especially given the small sample size.

Below is the summary of exploratory path analysis that investigated how different components of physical stability contribute to torso control during handstand performance on parallel bars. The study focused on four key variables: abdominal stability (SD Abd X), arm stability (SD Arm X), torso stability during floor handstands, and the outcome variable—torso stability on P-bars.

Table 6. Path Summary

Path	Type	Significance
SD Abd X → SD P-Bars Torso X	Direct	Significant
SD Arm X → SD P-Bars Torso X	Direct	Significant
SD Arm X → SD FHD Torso X → SD P-Bars Torso X	Mediation	Significant
SD Abd X → SD FHD Torso X → SD P-Bars Torso X	Mediation	Not significant
SD Arm X ✻ SD FHD Torso X → SD P-Bars Torso X	Moderation	Significant

SD Abd X ✻ SD FHD Torso X → SD P-Bars Torso X	Moderation	Not significant

Discussion

This study highlights the critical role of both abdominal and arm stability in enhancing torso control during handstand performance on parallel bars. The regression analysis confirmed strong, statistically significant direct effects from both predictors, underscoring the foundational importance of core and upper limb control in maintaining balance during complex gymnastic maneuvers. Mediation analysis revealed that torso stability on the floor significantly mediated the relationship between arm stability and P-bars performance. This suggests that effective arm control contributes to improved torso alignment during floor handstands, which subsequently enhances performance on apparatuses. In contrast, the mediation pathway from abdominal stability was not significant, indicating a more direct influence of core control on P-bars stability. Moderation analysis further demonstrated that the effect of arm stability on P-bars performance is amplified when torso control on the floor is high, emphasizing the importance of integrated upper-body coordination. No such moderating effect was observed for abdominal stability, suggesting that core strength contributes consistently, regardless of floor torso alignment. Bootstrapped confidence intervals validated the robustness of the direct and moderated effects involving arm stability, while confirming the non-significance of abdominal moderation. The path diagram visually distinguishes validated pathways (bold) from exploratory ones (dashed), reinforcing the central role of floor torso stability as both a mediator and moderator—particularly in relation to arm control. These findings support a multi-component model of gymnastic stability, where the torso functions not only as a stabilizing structure but also as a dynamic bridge that transmits and amplifies limb control to apparatus-based performance. This aligns with biomechanical theories of kinetic chain integration and offers practical implications for training strategies that emphasize coordinated core-limb engagement. Furthermore, the results strengthen previous research indicating that wrist flexors play a primary role in maintaining balance during handstands (Kochanowicz et al., 2018), reinforcing the importance of forearm strength and control. Overall, the data underscore the nuanced interplay between core and limb stability in shaping torso control and gymnastic performance on parallel bars.

However, the pathways through which these influences operate differ in complexity. Arm stability was shown to exert its effect not only directly but also indirectly through torso stability during floor handstands, with this mediation path statistically validated. Moreover, floor torso stability significantly moderated the relationship between arm control and P-bars performance, amplifying the effect as torso alignment improved. In contrast, abdominal stability maintained a consistent direct influence, unaffected by torso stability on the floor—its mediation and moderation paths were not statistically significant. These results suggest that torso stability functions as both a biomechanical bridge and amplifier, particularly in the transfer of arm control to apparatus-based performance, align with previous study that targeted postural training interventions have demonstrated positive effects on handstand execution quality in young gymnasts (Rohleder & Vogt, 2018a). Torso's dual role as mediator and moderator highlights its centrality in upper-body coordination during advanced gymnastic maneuvers. While the small sample size limits generalizability and needed to adequate to deliver a reasonable level of power (Koopman et al., 2015), the use of bootstrapping and non-parametric methods lends robustness to the key findings. Overall, this study provides a theoretically grounded framework for understanding stability dynamics in gymnastics and offers a foundation for future research using larger samples and longitudinal designs. Further suggestions to put into account in developing handstand in floor and P-bars are to break down handstand training into three distinct movement phases has proven more efficient than whole-movement training (Pradesh et al., 2017). A gymnast's ability to synchronize joint moment patterns during both training and competition depends heavily on coaching strategies that emphasize timing and technique. These training methods are designed to help athletes generate the necessary joint moments precisely when required throughout the movement sequence (Mizutori et al., 2021).

Notably, the lack of correlation between standing and handstand stability indices among juniors suggests that standing balance assessments may not reliably predict handstand proficiency during talent selection (Omorczyk et al., 2018). Additional findings support the efficacy of bio ceramic fabrics in enhancing postural control (Cian et al., 2015), and emphasize the value of combined tactile-verbal and visual-comparative feedback in motor learning, even over short-term interventions (Rohleder & Vogt, 2018b). The application of elastic tape has also been shown to improve handstand stability, likely through mechano-sensory stimulation, increased body awareness, and psychological belief in its effectiveness (Vinken & Heinen, 2015). Future research should expand the scope to include dynamic movements, utilize multiple indicators per latent variable, and explore the effects of innovative training equipment on skill acquisition and biomechanical efficiency (Herlambang et al., 2025). These directions will contribute to a more comprehensive understanding of handstand performance and support the continued evolution of gymnastics training methodologies.

Limitations

This study presents an exploratory path analysis of handstand gymnastics stability using sensor-derived data from 25 participants. While the findings offer valuable insights into the relationships among abdominal, arm, and torso stability across different handstand contexts, several limitations must be acknowledged. Firstly, the sample size (n = 25) is relatively small for multivariate statistical modeling, particularly for testing mediation and moderation effects (Mcneish & Mcneish, 2017). Although bootstrapping was employed to mitigate these risks and validate effect robustness, the results should be interpreted with caution and considered preliminary. Secondly, normality assumptions were violated across all variables, as confirmed by the Shapiro-Wilk test. While non-parametric methods (e.g., Spearman correlation) and bootstrapping were used to address this issue, the use of linear regression models may still be sensitive to these violations. Future studies should consider robust or Bayesian modeling approaches to better accommodate non-normal data distributions (Miočević et al., 2017). Also, the analysis revealed extremely high correlations among several variables, suggesting potential multicollinearity. This can inflate standard errors and complicate the interpretation of individual predictor effects. Dimensionality reduction techniques or regularized regression methods may be necessary in future research to address this issue. Finally, the study relied on cross-sectional data, limiting the ability to infer causality. Longitudinal designs or experimental interventions would be beneficial to confirm the directional relationships proposed in the path model. Despite these limitations, the study provides a theoretically grounded and methodologically transparent framework for understanding the biomechanical interplay of stability factors in gymnastics. The findings serve as a foundation for future research with larger samples and more advanced modeling techniques.

Conclusions

These results suggest that torso stability functions as both a biomechanical bridge and amplifier, particularly in the transfer of arm control to apparatus-based performance. Torso's dual role as mediator and moderator highlights its centrality in upper-body coordination during advanced gymnastic maneuvers. While the small sample size limits generalizability, the use of bootstrapping and non-parametric methods lends robustness to the key findings. Overall, this study provides a theoretically grounded framework for understanding stability dynamics in gymnastics and offers a foundation for future research using larger samples and longitudinal designs.

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