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Anatomical and functional asymmetry predicts G-force tolerance in high-Intensity physical performers

Kyu-Lim Lee[1,3], Jun-Young Sung[2,3] & Hee-Jin Kim[1]✉

Anatomical asymmetry is known to affect motor control and postural stability, but its impact under extreme physical stress, such as gravitational acceleration, remains underexplored. This study examined the association between anatomical asymmetry, functional movement patterns, occlusal force distribution, and G-force tolerance in Air Force cadets. Thirty male cadets underwent a G-force tolerance test using a human centrifuge. Functional asymmetry was assessed using the Functional Movement Screen (FMS), and occlusal force distribution was measured with a pressure-sensitive film system. Skeletal muscle mass was evaluated using bioelectrical impedance analysis. Participants were categorized into pass and fail groups based on G-test results. Group comparisons and multiple regression analyses were conducted to identify predictors of G-force performance. Skeletal muscle mass was significantly higher in the pass group, while other body composition variables showed no differences. The pass group outperformed the fail group in most FMS items, with the fail group showing greater bilateral imbalances in both FMS and occlusal force. Regression analysis identified significant associations between G-test outcomes and occlusal force parameters, and correlation analysis confirmed strong relationships with skeletal muscle mass and FMS scores, particularly the hurdle step. Functional and structural symmetries, especially movement patterns and occlusal balances, were associated with G-test outcomes, which serve as indirect indicators of tolerance to gravitational acceleration. Targeted interventions such as strength training and neuromuscular coordination exercises may be considered as potential strategies for future research to improve G-force tolerance and reduce injury risk in high-intensity physical activity populations.

Keywords Anatomical asymmetry, High-intensity physical activity, Functional movement screen (FMS), Occlusal force distribution, Skeletal muscle mass, Gravitational acceleration resistance

Abbreviation

FMS Functional movement screen

The ability to perform under high-intensity physical conditions is a critical factor in specialized populations that require exceptional motor function and physiological resilience. Exercises that enhance balance and body composition contribute to improved functional movement and increased resistance to high acceleration forces[1,2]. The musculoskeletal structures of the human body, particularly skeletal alignment and muscular balance, are intrinsically linked to movement patterns, with balance and symmetry playing pivotal roles in optimizing performance and reducing injury risk[3]. The human body continuously adapts throughout life, particularly in individuals subjected to intense physical training. Previous research has shown that professional athletes engaged in high-intensity training develop sport-specific anatomical adaptations that directly impact functional movement patterns[4].

Among specialized populations, military personnel, particularly Air Force cadets, undergo extreme physical demands that test their ability to withstand high G-forces. The G-test, which simulates high gravitational acceleration, serves as a key assessment of physical preparedness and neuromuscular control in these individuals[5].

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Few studies have integrated these factors into a unified model to predict tolerance to high gravitational forces. This knowledge gap is particularly evident in human aerospace research, which remains scarce due to limited access to military data. Given that fighter pilots must maintain optimal cognitive and physical performance under extreme stress, their functional symmetry and motor coordination are crucial determinants of success[6]. Prior studies indicate that cadets who successfully pass the G-test exhibit superior physical conditioning, neuromuscular coordination, and muscular endurance compared to those who fail[7].

One of the emerging factors influencing high-intensity performance is morphological symmetry, particularly in lower limb movement patterns and postural stability. Research utilizing the Functional Movement Screen (FMS) has demonstrated that lower limb symmetry significantly correlates with G-force resistance[8]. Our previous study demonstrated that adaptations of bite force and masseter muscle thickness to high-intensity training are associated with enhanced muscle activation and functional stability[9]. In addition, a study in golfers showed that occlusal stabilization improved driving distance performance, indirectly suggesting a functional link between occlusal balance and physical performance[10]. Other studies further demonstrated that occlusal balance influences motor function: modifications in dental occlusion affected postural stability and muscle activity[11], while the use of occlusal stabilization appliances enhanced masticatory muscle activation and athletic performance[12]. Similarly, experiments with elite marksmen demonstrated that maintaining a symmetric mandibular position led to enhanced postural control and precision, reinforcing the role of structural alignment in performance[13].

Given the necessity of functional balance and motor optimization in specialized populations, addressing asymmetry is fundamental not only for enhancing performance but also for reducing the risk of injury in high-intensity physical settings. While prior research has largely focused on isolated biomechanical factors, a more integrated approach—considering functional movement, skeletal muscle balance, and occlusal symmetry—is required to fully understand and improve high-G tolerance and overall physical resilience.

Our prior findings on occlusal adaptations to high-intensity training laid the groundwork for this study, which broadens the scope to investigate how anatomical asymmetries are associated with functional movement and G-test performance, used as an indirect measure of tolerance to gravitational acceleration, in Air Force cadets[14]. As a population requiring exceptional neuromuscular control and endurance, cadets provide a meaningful model for examining the interplay between structural asymmetry and high-performance demands. We hypothesized that cadets who successfully completed the G-test (pass group) would demonstrate (i) greater skeletal muscle mass, (ii) more symmetrical performance on the FMS, and (iii) more balanced occlusal force distribution compared to the fail group. By identifying key biomechanical predictors of G-test performance, this study offers practical insights for developing targeted training strategies that improve functional movement and prevent injury in both military and athletic contexts.

Methods

Thirty senior male cadets from the Republic of Korea Air Force Academy, a specialized population engaged in high-intensity physical activity, were recruited between May 15, 2023, and May 14, 2024. Given that more than 80% of cadets at the Korea Air Force Academy are male, we included only male cadets in order to ensure sample homogeneity and enhance the reliability of the results. All participants completed the G-test, an assessment designed to evaluate physiological and neuromuscular resilience under extreme gravitational acceleration. A power analysis using G-Power determined that a sample size of 34 participants was needed, based on an effect size of 0.25, an alpha level of 0.05, and a power of 0.80[15]. However, the final number of participants was limited due to voluntary participation constraints.

Participants were excluded if they declined to participate, had existing musculoskeletal injuries, or did not complete the G-test. All participants followed a standardized training regimen, including structured physical conditioning, departmental duties, regulated sleep schedules, and meal plans to ensure consistency in physical preparedness. Written informed consent was obtained from all participants before data collection. All study procedures were approved by the Ethics Committee of YongIn University (IRB No. 2-1040966-AB-N-01-2302-HSR-293-3) and the study was conducted according to the principles of the Declaration of Helsinki.

G-test measurement

The G-test was performed using a high-speed centrifuge gondola (ETC Corporate, Pennsylvania, USA) located at the Air Force Aerospace Medical Center within the Republic of the Korea Air Force Academy. Prior to testing, the procedures and breathing techniques were explained on the ground, and the assessment commenced once the participants' heart rates had stabilized. During the test, the participants were seated in a cockpit-style seat and a belt that secured only the body had to endure 5 G of acceleration for 30 s. The gondola began at 0.8 G and accelerated to 5 G upon lever activation by the participant. During the test, the instructor recorded the time at 10-second intervals and provided continuous verbal cues to maintain cervical elevation and prevent postural collapse. The test was administered a single time, and participants were classified into two outcome groups: the pass group, comprising those who withstood 30 s, and the fail group, comprising those who either failed to complete the 30 s or experienced G-induced loss of consciousness (G-LOC). As a result of the test, participants were divided into a pass group (n, 17) and a fail group (n, 13).

FMS measurement

FMS assessments were conducted two weeks prior to the G-test. As the participants had not undergone the G-test, they were unaware of their group assignment at the time of measurement. Measurement and evaluation were performed and evaluated by experts who had received FMS measurement training, and the measurement participants received training on the measurement method in advance[16]. Before testing, participants were

thoroughly briefed on the seven movements and their corresponding scoring criteria. The tests included the deep overhead squat, hurdle step, inline lunge, trunk stability push-up, active straight leg raise, shoulder mobility, rotary stability and total score.

To evaluate symmetry, five movements (hurdle step, inline lunge, active straight leg raise, shoulder mobility, and rotary stability) were analyzed by comparing right- and left-side performances. Each movement was scored on a scale of 0 to 3, where 0 indicated the lowest performance and 3 indicated the highest performance. The pain experienced during the assessment resulted in a score of 0. A score of 1 was assigned if the participant could not complete the movement or if it was performed incorrectly. A score of 2 indicated that the movement was completed but with some compensatory mechanisms. A score of three represented normal performance without any compensation. The overall score was defined as the lowest score recorded for either side. The scores were directly compared by evaluating performance on both sides, and asymmetry was defined by contrasting the two sides based on the measured reference scores. However, no further assessment of corrective exercises was performed.

Bite force assessment with an occlusal force analysis system

Bite force was measured at the same location immediately after the FMS assessment. Normal occlusion was confirmed prior to testing based on participants' self-reported dental history. Bite force was measured using a Dental Prescale sheet. The participants with normal occlusion completed two practice trials while sitting in a natural posture without head support. Participants were instructed to bite with maximum intercuspation without head support. For the actual measurement, the participants bit down on a sheet placed between their upper and lower teeth with maximum force for 3 s. The occlusal contact area was recorded by bursting the microcapsules onto the sheet. The analyzed parameters included occlusal contact area (mm^2), average occlusal pressure (MPa), maximum occlusal pressure (MPa), and total occlusal force (N).

The total bite force and the forces exerted on the right and left sides were analyzed using Occluser (Occluser 709; GC, Tokyo, Japan; https://www.gc.dental) (Fig. 1). The Dental Prescale sheet is pre-calibrated by the manufacturer, and no additional calibration was required. Because all sheets were processed and analyzed by the same trained examiner using the automated Occluser software, inter-rater variability was not applicable. Intra-rater reliability was ensured by repeating each measurement twice and using the mean value.

Masseter muscle thickness evaluation via ultrasonography

Masseter muscle thickness was measured using a real-time 2D B-mode ultrasound device equipped with a high-frequency linear array transducer (SONON 500; Healcerion Co., Ltd., Seoul, South Korea). The transducer was positioned in the short-axis orientation with light contact, without a standoff pad, to minimize tissue compression. Imaging was performed at a depth of 3 cm using a 10-MHz linear transducer (gain = X dB, dynamic range = Y). The muscles were identified by palpation during repeated relaxation and clenching. A reference line from the cheilion to the otobasion inferius was used to standardize anatomical positioning, and measurements were performed along this line.

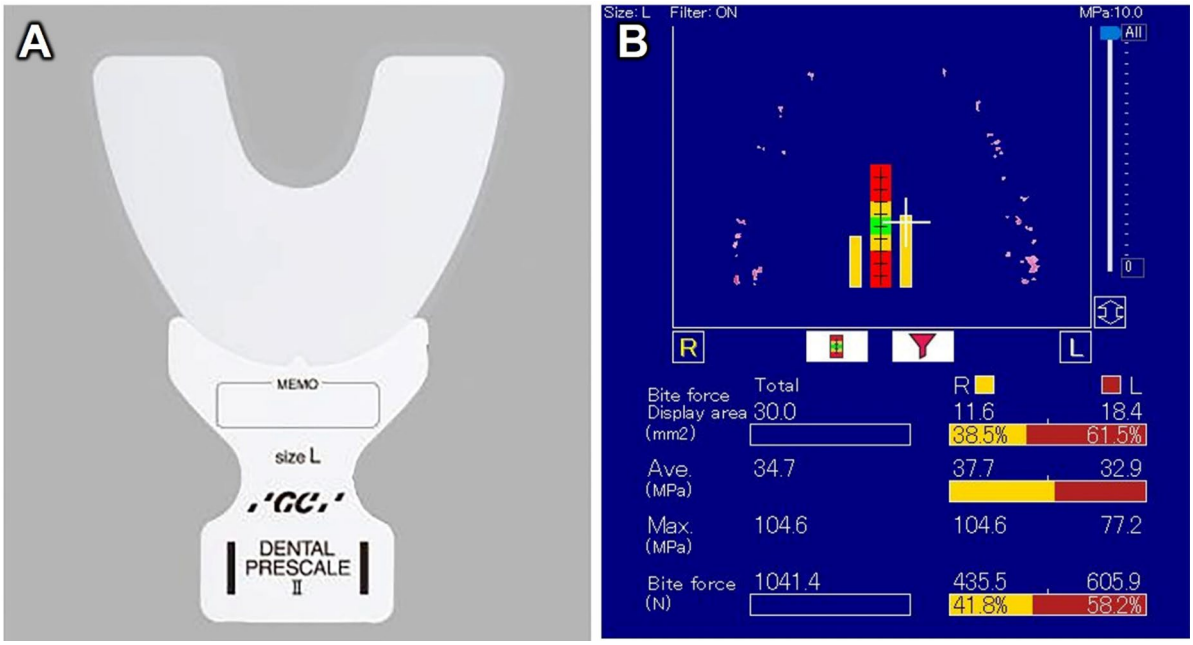

Fig. 1. Bite force assessment with an occlusal force analysis system. (**A**) A Dental Prescale sheet was used to measure occlusal force. The sheet records the occlusal contact area through the bursting of microcapsules. (**B**) Visualization of bite force data using an analyzing system, showing total bite force and force distribution on the right and left sides.

Each measurement was repeated twice, and the mean thickness was calculated. All images were obtained and analyzed by a single examiner with extensive prior experience in head and neck ultrasonography, eliminating inter-rater variability. Intra-rater reliability was ensured by repeated measures and averaging. ImageJ software (version 1.54k; National Institutes of Health, Bethesda, MD, USA; https://imagej.net/ij/) was used for thickness analysis. Transducer orientation, anatomical landmarks, and representative images of the measurement protocol are illustrated in Fig. 2. This ultrasonography protocol follows the same standardized short-axis imaging approach that was previously validated in our group's study of professional athletes[14].

Body composition measurement

Body composition was assessed five days prior to the G-test. Participants were instructed to avoid strenuous physical activity and to obtain adequate sleep the night before the assessment. Measurements were conducted at 08:00 h under fasting conditions. Body weight, skeletal muscle mass, body fat mass, body fat percentage, and

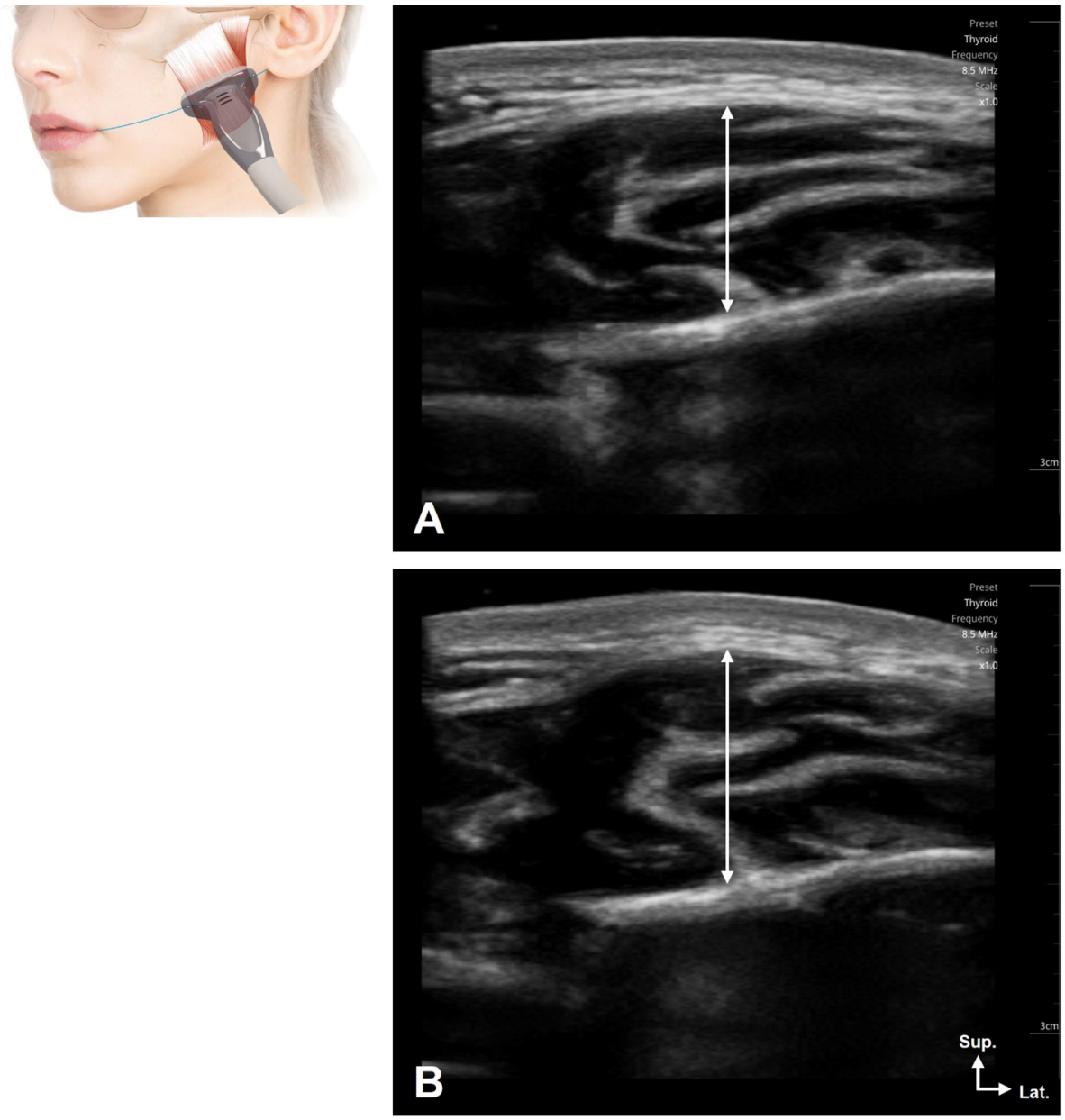

Fig. 2. Ultrasonographic assessment of masseter muscle thickness. (**A**) Measurement in the resting state. (**B**) Measurement during maximal voluntary clenching. Sup, superficial; Lat., lateral. The representative ultrasonographic images were obtained using SONON 500 (Healcerion Co., Ltd., Seoul, South Korea) and analyzed using ImageJ (version 1.54k; National Institutes of Health, Bethesda, MD, USA; https://imagej.net/ij/). The figure layout and illustration were prepared using Adobe Photoshop (Adobe Inc., version 23.5; https://www.adobe.com).

body mass index were obtained using the InBody 720 analyzer (Biospace Co., Ltd., Seoul, Republic of Korea), while height was measured using a standard stadiometer.

Quantification and statistical analysis

Data collection and statistical analyses were conducted from November 29 to December 10, 2024. Descriptive statistics, including mean values and standard deviations, were calculated using SPSS version 28 (IBM Corp., Armonk, NY, USA). Differences between G-test pass and fail groups were analyzed using independent t-tests to determine significant biomechanical and physiological predictors of performance. While within-group left–right imbalances were analyzed using paired t-tests. In addition, Cohen's *d* effect size was calculated using the pooled standard deviation of the change scores, with values less than 0.2 interpreted as small, values of 0.5 or greater as medium, and values of 0.8 or greater as large effects. Multiple regression analysis was employed to examine the relationships between body composition, fatigue, occlusal force, and G-test outcomes. Regression analysis included model fit indices, R^2 and adjusted R^2 change, as well as the Durbin–Watson statistic and multicollinearity diagnostics. In addition, we used variance inflation factor (VIF) diagnostics to identify and mitigate multicollinearity, improving the stability and interpretability of the regression estimates Pearson's correlation analysis was conducted to assess associations between key variables. For the correlation coefficient (r), the strength of the association was classified as follows: < 0.10, very weak; 0.10–0.29, weak; 0.30–0.49, moderate; 0.50–0.69, strong; 0.70–0.89, very strong; and ≥0.90, almost perfect. Statistical significance was set at $p < 0.05$.

Results

Participant characteristics

Table 1 shows the physical characteristics of the participants. Body composition analysis revealed a statistically significant difference in skeletal muscle mass between the pass and fail groups (*effect size*, 1.1; $p = 0.010$). There were no statistically significant differences in other variables, including age, height, weight, body fat mass, and BMI.

FMS measurements

Analysis of left- and right-side FMS scores according to G-test outcomes indicated that the pass group outperformed the fail group in all items except shoulder mobility. Statistically significant differences were observed for the right hurdle step (*effect size*, 0.7; $p = 0.008$), left hurdle step (*effect size*, 0.7; $p = 0.005$), left inline lunge (*effect size*, 0.4; $p = 0.018$), and right active straight leg raise (*effect size*, 0.4; $p = 0.002$).

Analysis of left- and right-side FMS measurements according to G-test outcomes revealed that, on average, the fail group exhibited greater bilateral imbalances compared to the pass group across most items. Notably, a statistically significant imbalance was observed in the Active Upright Leg test (*effect size*, 0.7; $p = 0.013$) (Fig. 3).

Occlusal force measurements

The difference in left and right occlusal forces according to the G-test results was also found to have a left–right imbalance difference in the failure group compared to the pass group in all measurements, especially particularly in bite force distribution under rest and clenching conditions, including occlusal area (mm^2) and pressure (MPa). In addition, both the pass and fail groups showed significant differences in area (mm^2) (pass, $p = 0.031$; fail, $p = 0.043$), maximum MPa (pass, $p = 0.022$; fail, $p = 0.021$), and force (pass, $p = 0.020$; fail, $p = 0.017$; Fig. 4).

Regression and Pearson's correlation analysis

Table 2 shows the G-test and regression analysis results for the unbalanced measurement factors. In the case of the FMS, the G-test results and statistical significance are not shown. On the other hand, for occlusal force, statistical significance was confirmed in area left (B, 0.458; β, 2.702; t, 2.293; $p = 0.036$), and force total (B, − 0.012; β, − 4.692; t, − 2.191; $p = 0.044$). The model demonstrated an R^2 of 0.435, a Durbin–Watson statistic of 1.207, and all VIF values were below 5, indicating no concerning multicollinearity. Finally, the results of the correlation analysis showed that the G-test results had a statistically significant correlation with skeletal muscle mass (r, − 0.463; $p = 0.010$), hurdle step (r, − 0.659; $p < 0.001$), inline lunge (r, − 0.365; $p = 0.047$), active straight leg raise (r, − 0.446; $p = 0.033$), and total score (r, − 0.513; $p = 0.004$). Correlation analysis indicated that the G-test results

Variable	Pass (*n*, 17)	Fail (*n*, 13)	F	t	C	*p*
Age (year)	23.06 ± 0.42	23.23 ± 0.43	1.326	-1.078	-0.1	0.290
Height (cm)	174.11 ± 3.44	173.76 ± 2.95	0.461	0.293	0.1	0.772
Weight (kg)	73.61 ± 7.44	68.64 ± 5.87	0.529	1.978	0.7	0.058
Skeletal muscle mass (kg)	**36.03 ± 2.97**	**33.05 ± 2.84**	**0.091**	**2.766**	**1.1**	**0.010****
Body Fat mass (kg)	10.46 ± 4.37	10.47 ± 2.33	6.084	0.000	-0.1	1.000
Body Mass index (m)	24.29 ± 2.64	22.73 ± 1.77	1.175	1.837	0.7	0.077
Body Fat mass (%)	13.97 ± 4.76	15.18 ± 2.71	5.990	-0.818	-0.3	0.420

Table 1. Descriptive statistics of participant characteristics based on G-test results. *Values are expressed as mean ± SD ** p < 0.01 by t-test; C, Cohen's effect size*

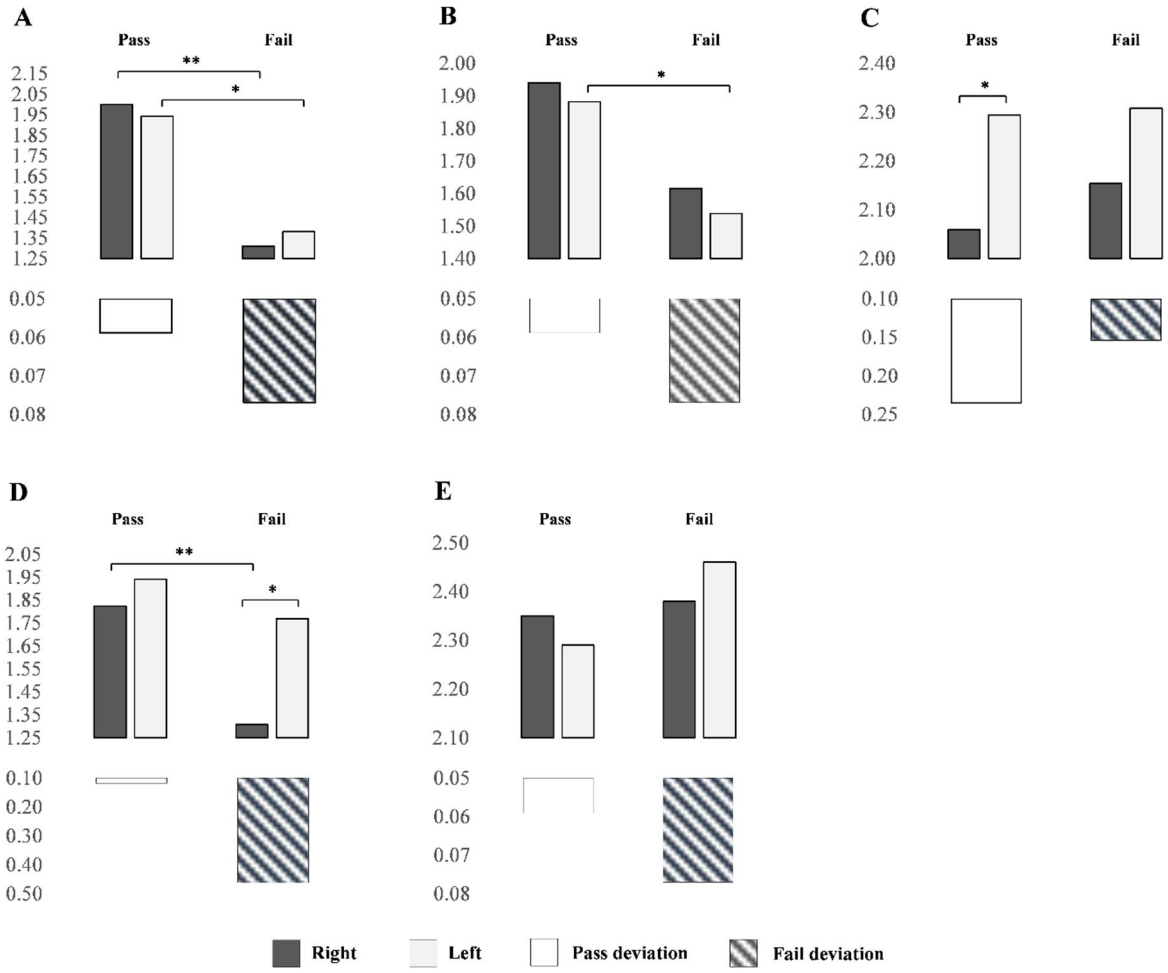

Fig. 3. Functional movement screen (FMS) analysis t-test results based on the gravitational acceleration (G-test) results. (**A**) Hurdle step; (**B**) Inline lunge; (**C**) Shoulder mobility; (**D**) Active straight leg raises; (**E**) Rotary stability; Pass, G-test pass group; Fail, G-test fail group; * $p< 0.05$, ** $p< 0.01$ by t-test

were strongly associated with the hurdle step, followed by the total FMS score, active straight leg raise, and skeletal muscle mass (Table 3).

Discussion

This study examined the role of anatomical symmetry in high-intensity physical performance, focusing on Air Force cadets as a specialized population exposed to extreme physical demands. Unlike previous studies that primarily assessed athletes or general military personnel, this study investigated the association between structural and functional asymmetries and G-test outcomes, which serve as an indirect indicator of tolerance to gravitational acceleration. Functional asymmetries have been associated with impairments in motor control, reduced functional movement, and an increased risk of performance failure and physical strain in high-stress conditions[16,17]. Prior research has indicated that skeletal muscle mass and joint mobility asymmetries can negatively affect movement patterns and result in compensatory mechanisms that may contribute to injury susceptibility[18]. Studies on athletes have also demonstrated that high-intensity training without targeted interventions to address asymmetry can exacerbate functional imbalances and limit performance[8].

In our results, cadets who passed the G-test exhibited greater symmetry in FMS scores and occlusal force, as well as higher skeletal muscle mass, suggesting that greater functional balance and muscular development may be associated with better G-test outcomes. The Pearson correlation analysis further demonstrated the relationship between the G-test and FMS outcomes. In particular, significant negative correlations were identified in items such as the hurdle step, in-line lunge, shoulder mobility, and active straight leg raise, which are subject to left–right side analysis. Additionally, skeletal muscle mass was significantly higher in the pass group, highlighting its role in maintaining stability and endurance under extreme physical stress. In contrast, the fail group exhibited greater asymmetries in functional movement and occlusal force distribution, which may be related to reduced neuromuscular coordination and postural control under high-G exposure. These imbalances may have compromised controlled movement, contributing to G-test failure.

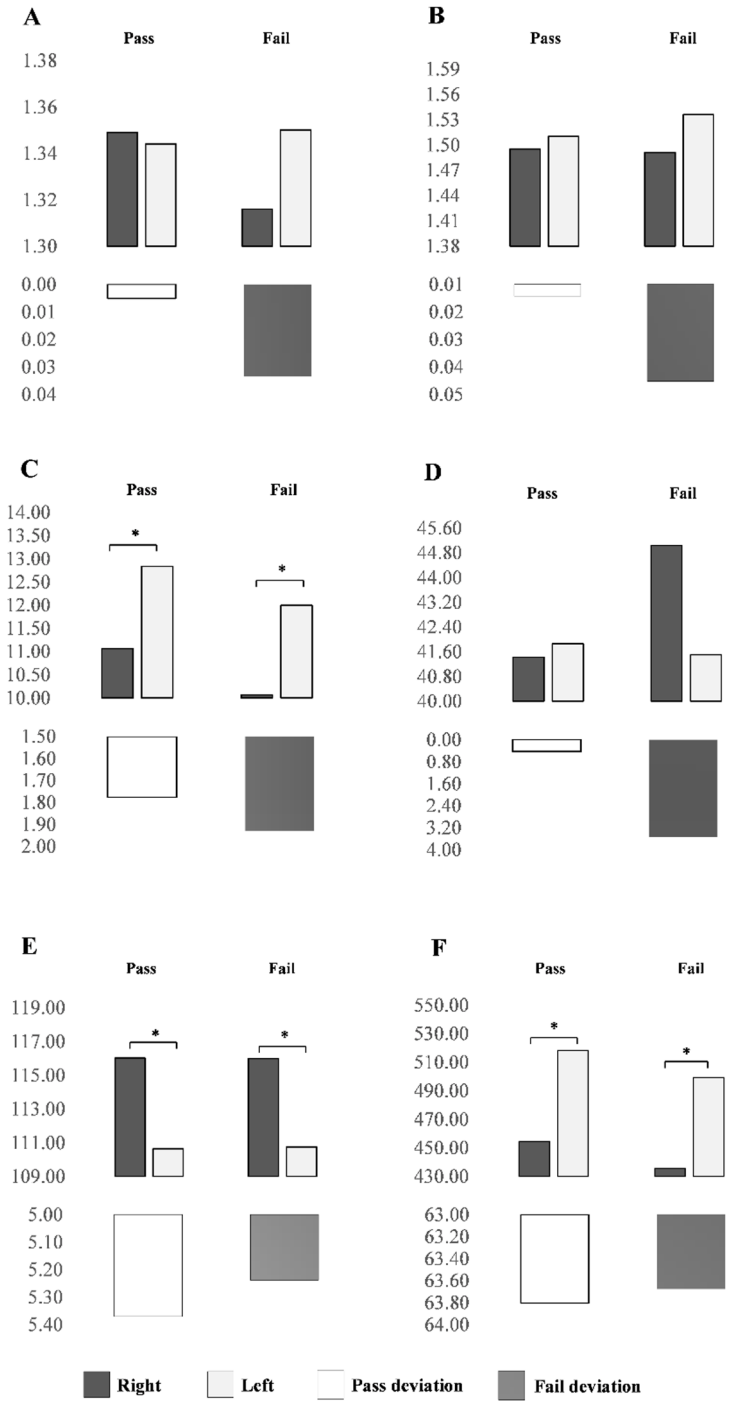

Fig. 4. Analysis of occlusal force based on the gravitational acceleration (G-test) t-test result. (**A**) Masseter muscle thickness at rest; (**B**) Masseter muscle thickness during clenching; (**C**) Occlusal contact area (mm^2); (**D**) Average occlusal force (MPa); (**E**) Maximum occlusal force (MPa); (**F**) Total occlusal force (N); Pass, G-test pass group; Fail, G-test fail group; * $p < 0.05$, by t-test.

The findings emphasize the necessity of addressing functional asymmetries through structured training programs. Previous research has shown that resistance training and neuromuscular conditioning can mitigate the negative effects of asymmetrical movement patterns, enhance motor function and reduce injury risk[19]. Weight training and exercises targeting postural control have been reported to improve structural symmetry, particularly in populations engaged in unilateral or high-intensity physical activities[20]. In this study, occlusal force and masseter muscle thickness were examined as additional components of postural stability. Consistent with prior findings, our results confirmed that imbalances in occlusal force were associated with neuromuscular coordination deficits, as indicated by a moderate positive influence in the left occlusal area (B, 0.458) and a

Variable	Model			
	B	β	t	*p*
(Constant)	2.67	-	2.285	0.033
Deep squat	-0.045	-0.055	-0.074	0.942
Hurdle step	-0.387	-0.51	-1.497	0.149
Inline lunge	-0.094	-0.099	-0.124	0.902
Shoulder mobility	0.100	0.124	0.278	0.784
Active straight leg raises	-0.197	-0.208	-0.309	0.76
Trunk stability push-up	-0.05	-0.058	-0.136	0.893
Rotary stability	-0.074	-0.072	-0.189	0.852
Total score	0.010	0.041	0.020	0.984
R^2, 0.479	*$_{adj}R^2$, 0.281*	*DW, 1.074*	*F, 2.414*	*p* = 0.051
(Constant)	3.464	-	0.797	0.437
Masseter right (resting)	3.186	0.733	1.399	0.181
Masseter right (clenching)	-1.572	-0.365	-0.788	0.442
Masseter left (resting)	-1.402	-0.339	-0.683	0.504
Masseter left (clenching)	-0.566	-0.142	-0.286	0.778
Area right (mm2)	-0.711	-3.6	-1.783	0.094
Area left (mm2)	**0.458**	**2.702**	**2.293**	**0.036***
Ave. right (MPa)	-0.312	-2.951	-1.788	0.093
Ave. left (MPa)	-0.114	-1.05	-0.514	0.614
Ave. total (MPa)	0.349	2.826	0.927	0.368
Max. right (MPa)	0.013	0.192	0.507	0.619
Max. left (MPa)	0.015	0.305	0.667	0.514
Force total (N)	**-0.012**	**-4.692**	**-2.191**	**0.044***
R^2, 0.435	*$_{adj}R^2$, -0.025*	*DW, 1.207*	*F, 0.946*	*p* = 0.534

Table 2. Multiple regression analysis between G-test results and unbalanced measurement factors. *Significant difference *p < 0.05; Independent variable, G-test results; DW, Durbin-Watson; Ave., Average; Max., Maximum*

Variable	G-test	SMM	DS	HS	IL	SM	ASLR	TSPU	RS	TS
G-test	-		-		-		-		-	
SMM	− 0.463**									
DS	-0.259	0.128	-		-		-		-	
HS	− 0.659***	0.324	0.308							
IL	− 0.365*	-0.050	0.160	0.391*	-		-		-	
SM	-0.004	-0.195	0.299	0.116	0.121					
ASLR	− 0.494**	0.068	0.481**	0.587***	0.388*	0.329	-		-	
TSPU	-0.233	0.134	0.387*	0.177	0.221	-0.094	0.443*			
RS	0.033	-0.023	-0.359	0.021	0.110	-0.064	− 0.420*	− 0.599***	-	
TS	− 0.513**	0.070	0.686***	0.635***	0.699*	0.448*	0.794***	0.456*	-0.183	

Table 3. Correlation coefficients between G-test results and skeletal muscle mass and functional movement test variables. *Significant difference, *p < 0.05, **p < 0.01, ***p < 0.001; G-test, G-test results; SMM, Skeletal muscle Mass; DS, deep squat; HS, hurdle step; IL, inline lunge; SM, shoulder mobility; ASLR, active straight leg raises; TSPU, trunk stability push-up; RS, rotary stability; TS, total score*

negative association with total force (B, − 0.012). In the multivariable models, negative coefficients indicate an inverse partial association after adjustment for all covariates. Total occlusal force showed a negative coefficient with the G-test result, meaning that, holding other predictors constant, higher occlusal force is associated with a lower G-test result. On a standardized scale, a 1-SD increase in occlusal force corresponded to a B, − 0.012 and β = -4.692 change in G-test result. These outcomes align with previous research demonstrating that balanced occlusal force distribution is linked to improved postural control and muscle activation[11,12]. Furthermore, our findings expand upon earlier observations of occlusal asymmetry in athletes[13], suggesting that oral functional asymmetry may have broader implications for whole-body neuromuscular performance under extreme physical conditions. Because our data is observational and no occlusal interventions were tested, any practical applications—including customized mouthguards—should be treated strictly as hypotheses for future investigation. Confirmatory interventional studies are required before drawing conclusions about efficacy.

Functional asymmetries may contribute to chronic physical strain and an increased risk of injury in individuals subjected to repetitive high-intensity conditions. Neuromuscular training, postural corrections, and targeted strength conditioning may enhance physical resilience and performance optimization in specialized populations such as Air Force cadets. Expanding this research to a broader range of high-intensity occupations and activities is necessary to establish comprehensive training protocols. Future studies should investigate the relationship between functional symmetry, neuromuscular coordination, and performance outcomes in physically demanding professions. Additionally, further research is required to refine training methodologies that prioritize postural stability and functional movement, which may lead to improved performance and injury prevention.

This study has several limitations, including the relatively small sample size, the inclusion of only male participants, and its cross-sectional design, which does not permit causal inference. These constraints may limit the generalizability of the findings. Future studies should adopt longitudinal or interventional designs with larger, mixed-sex cohorts to validate and extend these results.

Conclusion

This study highlights the potential importance of anatomical symmetry in optimizing physical performance under high-intensity conditions. Structural and functional balance was associated with G-test outcomes, which indirectly reflect tolerance to gravitational acceleration. Functional movement symmetry, occlusal force balance, and skeletal muscle mass were key factors associated with successful G-test performance among Air Force cadets. Cadets who passed the G-test demonstrated greater structural and functional balance, supporting the relationship between physical symmetry and favorable G-test outcomes.

Targeted interventions aimed at reducing asymmetries—such as neuromuscular training, postural corrections, and balanced strength conditioning— may be considered candidate strategies to be evaluated in future research. Additionally, the observed association between occlusal force balance and G-test success suggests that oral and maxillofacial factors may influence overall postural stability and motor function.

Future research should expand on these findings by including larger and more diverse populations and examining additional biomechanical and neuromuscular factors. A better understanding of the relationship between functional symmetry, functional movement, and high-intensity performance may facilitate the development of optimized training regimes for both military and athletic populations.

Data availability

The datasets generated and/or analyzed during the current study were obtained from cadets of the Republic of Korea Air Force Academy and are subject to national security restrictions. As a result, the raw individual-level data cannot be deposited in a public repository. However, de-identified summary data (group-level means, standard deviations, and effect sizes), together with the statistical analysis scripts, are available from the corresponding author upon reasonable request. Access to the complete dataset may be considered on a case-by-case basis, subject to review and approval by the Republic of Korea Air Force under a formal Data Use Agreement.

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Author contributions
Overall planning of the research, data acquisition, creation of key results, analysis and interpretation, and major drafting and revision of manuscript submission was done by K.-L. L.; data acquisition, analysis and interpretation, and major drafting and revision of manuscript submission, J.-Y. S.; Overall organization and direct supervision of the research was undertaken by H.-J. K.

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Declarations

Competing interests
The authors declare no competing interests.

Ethics approval and consent to participate
All study procedures were approved by the Ethics Committee of YongIn University (IRB No. 2-1040966-AB-N-01-2302-HSR-293-3) and the study was conducted according to the principles of the Declaration of Helsinki.

Additional information
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