

# Structural and functional asymmetry of the lower limb related to gravitational acceleration tolerance

## Highlights

- G-test-fail cadets showed thinner medial femoral cartilage in the right knee
- G-test-pass cadets had greater knee strength and reduced flexor asymmetry at 180°/s
- Lower-limb structural and functional asymmetry related to reduced +Gz tolerance
- Ultrasonography, isokinetic tests, and FMS help screen cadets at injury risk

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## In brief

Human physiology



## Article

# Structural and functional asymmetry of the lower limb related to gravitational acceleration tolerance

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## SUMMARY

This study investigates the physiological effects of intensive physical training on femoral cartilage morphology and limb asymmetry in strength in air force cadets. Thirty male cadets were evaluated using ultrasonography to measure femoral cartilage thickness, isokinetic testing to assess knee flexor and extensor strength, and the functional movement screen (FMS) to examine movement patterns. Participants were divided into pass and fail groups based on the G test, a measure of gravitational acceleration tolerance. Cadets in the fail group exhibited significantly thinner cartilage in the medial condyle of the right knee and greater knee flexion asymmetry at 180°/s. The pass group demonstrated superior FMS performance, greater muscular strength, and less limb asymmetry. These findings suggest that repetitive mechanical loading during military training may lead to cartilage thinning and functional asymmetry, increasing the risk of musculoskeletal injury. Periodic musculoskeletal screening and targeted interventions could mitigate injury risks in occupational environments characterized by high physical demands.

## INTRODUCTION

Articular cartilage plays a vital role in joint function due to its viscoelastic properties, allowing it to absorb impact forces, minimize friction, and facilitate smooth movement.<sup>1–4</sup> This thin connective tissue (2–4 mm thick) covers the ends of long bones and is composed of 60%–80% water and 20%–40% solid components, including collagen and proteoglycans.<sup>1</sup> These components enable cartilage to distribute mechanical loads efficiently and protect underlying bone structures.<sup>2</sup> However, prolonged or repetitive mechanical loading can compromise cartilage integrity and accelerate degeneration.<sup>5</sup> During loading, fluid exudation occurs, followed by rehydration and structural restoration during recovery—processes essential for maintaining joint health.<sup>6–9</sup> The short-term response of cartilage to mechanical stress is increasingly recognized as a key indicator of long-term adaptation and resilience.<sup>10</sup>

Previous research has examined how exercise type, intensity, and frequency influence cartilage deformation.<sup>6,11–13</sup> Studies comparing aerobic and resistance exercises have found that cartilage deformation is proportional to the magnitude of mechanical stress applied.<sup>14</sup> In our previous study, we investigated femoral cartilage adaptation to different mechanical stress patterns in athletes, comparing weightlifters and wrestlers. The find-

ings revealed that weightlifters, who performed controlled symmetrical movements with high-magnitude compressive loads, exhibited thicker and more uniform cartilage. In contrast, wrestlers, who engage in highly asymmetrical and multidirectional movements, displayed greater left-right imbalances and thinner cartilage, particularly in the dominant knee. These results underscore the significant role of movement patterns in cartilage adaptation and functional asymmetry.

Despite these insights, long-term cartilage adaptations in military personnel remain largely unexplored, even though soldiers are subjected to distinct biomechanical stresses compared to athletes. Unlike structured sports training, which optimizes performance while minimizing injury risk, military training involves prolonged and unpredictable mechanical stress on the lower extremities due to long-distance marching, repetitive drills, and prolonged combat boot use.<sup>15</sup> Ultrasonography provides a cost-effective and noninvasive alternative to magnetic resonance imaging for evaluating femoral cartilage thickness and cross-sectional area.<sup>16</sup> This study employed ultrasonography, isokinetic knee strength testing, and the functional movement screen (FMS) to examine the relationships between femoral cartilage structure, knee joint function, and movement patterns in cadets.

Femoral cartilage deformation occurs in response to mechanical loading; however, once a threshold is reached, no further



**Table 1. Demographic characteristics and functional movement screen (FMS) results of participants**

Variable	Pass group	Fail group	F	t	p
Age (year)	23.06 ± 0.42	23.23 ± 0.43	1.326	-1.078	0.290
Height (cm)	173.34 ± 2.91	174.76 ± 3.46	0.560	-1.225	0.115
Weight (kg)	72.84 ± 8.17	69.66 ± 5.32	2.239	1.215	0.117
Skeletal muscle mass (kg)	35.69 ± 3.28*	33.50 ± 2.83	0.647	1.917	0.033
Body fat mass (kg)	10.39 ± 4.34	10.58 ± 2.42	7.565	-0.142	0.440
Body mass index (kg/m <sup>2</sup> )	24.23 ± 2.73	22.82 ± 1.68	1.710	1.644	0.056
Deep squat	13.99 ± 4.58	15.15 ± 3.07	5.290	0.783	0.220
Hurdle step	2.06 ± 0.66**	1.46 ± 0.52	0.167	2.690	0.006
Inline lunge	1.94 ± 0.56	1.69 ± 0.48	0.523	1.287	0.104
Shoulder mobility	2.18 ± 0.64	2.31 ± 0.63	0.134	-0.562	0.289
Active straight leg raises	1.94 ± 0.56	1.69 ± 0.48	0.523	1.287	0.104
Trunk stability push-up	2.18 ± 0.53*	1.77 ± 0.60	0.459	1.974	0.029
Rotary stability	2.35 ± 0.49	2.38 ± 0.51	0.114	-0.172	0.432
Total score	14.59 ± 1.94	13.31 ± 2.06	0.004	1.747	0.092

Values are expressed as mean ± SD, \* $p < 0.05$ , \*\* $p < 0.01$ .

adaptation occurs.<sup>17</sup> Military personnel, particularly fighter pilots, experience lower limb imbalances due to exposure to extreme gravitational acceleration (G force), requiring high-intensity training to maintain neuromuscular stability.<sup>18</sup> Similarly, military cadets are exposed to chronic, asymmetrical mechanical stress resulting from long-distance running, heavy load carriage, and prolonged combat boot wear—factors that contribute to joint stress and asymmetry.<sup>19,20</sup> Furthermore, studies have shown that lower limb strength and balance are crucial for pilots to counteract the effects of G-force exposure.<sup>21</sup>

Although mechanical loading has been widely studied in athletes, its long-term effects on cartilage adaptation in military personnel remain largely unknown. Given the unique biomechanical demands of military training, this study aimed to analyze femoral cartilage thickness, lower limb strength asymmetry, and movement patterns in cadets. By doing so, we sought to provide clinically relevant insights into cartilage health and injury prevention in populations exposed to high-intensity physical stress.

## RESULTS

### Body composition and FMS analysis results

Skeletal muscle mass was significantly higher in the pass group than in the fail group (*effect size*, 0.7;  $p = 0.033$ ). The pass group also demonstrated superior performance in the hurdle step (*effect size*, 1.0;  $p = 0.006$ ) and trunk stability push-ups (*effect size*, 0.7;  $p = 0.029$ ) components of the FMS. No significant differences were observed in other body composition metrics or FMS scores (Table 1).

### Femoral cartilage thickness

Cadets in the fail group exhibited significantly thinner femoral cartilage, particularly in the medial condyle of the right knee (*effect size*, 1.2;  $p = 0.039$ ), with greater mediolateral cartilage thickness difference in both knees (right, *effect size*, 1.3;  $p < 0.001$ ; left, *effect size*, 0.9;  $p < 0.001$ ). In contrast, the pass group demonstrated minimal asymmetry, except for a significant differ-

ence in the medial condyle of the left knee (*effect size*, 1.7;  $p = 0.001$ ) (Figure 1; Table 2).

The mean femoral cartilage thickness values for each condyle were as follows. In the pass group, the medial condyle of the right knee measured  $1.63 \pm 0.38$  mm, while the lateral condyle measured  $1.81 \pm 0.27$  mm. In the left knee, the medial condyle measured  $1.49 \pm 0.48$  mm, and the lateral condyle measured  $1.87 \pm 0.27$  mm. In the fail group, the medial condyle of the right knee measured  $1.39 \pm 0.29$  mm, and the lateral condyle measured  $1.80 \pm 0.34$  mm. For the left knee, the medial condyle measured  $1.36 \pm 0.26$  mm, while the lateral condyle measured  $1.91 \pm 0.37$  mm.

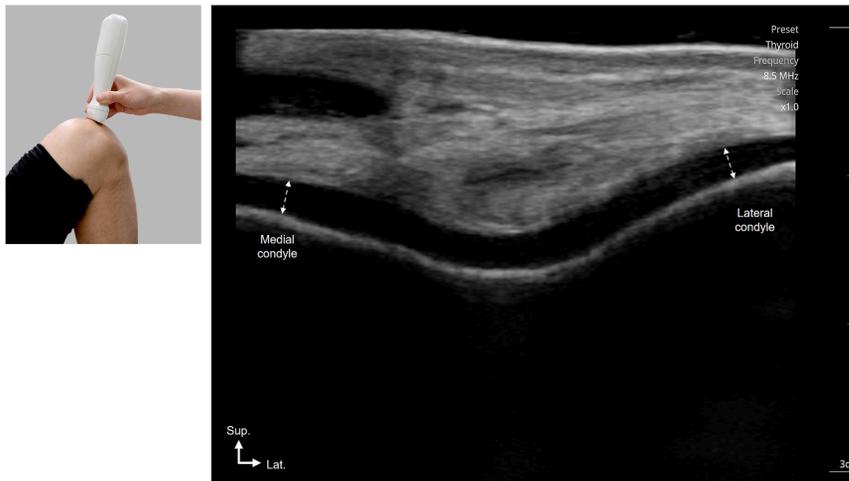
### Isokinetic strength test

Isokinetic strength measurements differed significantly between the pass and fail groups across all recorded parameters, including average power, peak power, peak power relative to body weight, and total work. At 60°/s, significant differences were observed in the average power of knee flexion for both the right and left legs (*effect size*, 1.3;  $p = 0.001$ ), peak power of left knee extension (*effect size*, 1.4;  $p = 0.001$ ), and total work of the right knee (*effect size*, 1.5;  $p < 0.001$ ). At 180°/s, the pass group exhibited significantly greater average power (*effect size*, 1.3;  $p = 0.001$ ) and peak power (*effect size*, 1.7;  $p = 0.001$ ) of the right knee. At 240°/s, substantial differences in peak power were observed between the right and left knee extensions (right, *effect size*, 1.5;  $p < 0.001$ ; left, *effect size*, 1.2;  $p = 0.001$ ), indicating greater strength symmetry in the pass group than in the fail group (Figure 1; Table 3).

### Limb asymmetry in strength

The pass group demonstrated minimal left-right imbalance, with a significant difference observed only in knee extension peak power relative to body weight at 60°/s (*effect size*, 1.3;  $p = 0.013$ ).

In contrast, the fail group exhibited pronounced limb asymmetry, with significant left-right imbalances in knee flexion at 180°/s (*effect size*, 1.5;  $p = 0.018$ ), flexion peak power relative to body



**Figure 1. Ultrasonographic image illustrating the assessment of femoral cartilage thickness**

A high-frequency linear transducer was positioned transversely over the anterior knee. The cartilage thickness was determined by measuring the linear distance from the cartilage-bone interface to the synovial space-cartilage interface.

In addition, Air Force pilots who continue to perform high-intensity physical activities, such as resistance to gravitational acceleration, are classified into occupational groups that clearly show the effects of human asymmetry.<sup>22</sup> This study examined the effects of intensive military training on femoral cartilage morphology, knee-joint function, and

weight (*effect size*, 1.5;  $p = 0.017$ ), and average power of knee flexion (*effect size*, 1.7;  $p = 0.046$ ). Additionally, the fail group demonstrated significant total work (*effect size*, 1.2;  $p = 0.039$ ) at  $240^\circ/\text{s}$ . These findings suggest that cadets in the fail group experienced greater lower limb asymmetry, particularly at higher angular velocities (Figure 2; Table 4).

## DISCUSSION

Articular cartilage is a specialized connective tissue that facilitates smooth, low-friction joint movement while absorbing and distributing mechanical loads. Its extracellular matrix, primarily composed of type II collagen, proteoglycans, and water, enables it to withstand compressive and shear forces. However, its avascular nature limits its repair capacity, making it susceptible to cumulative mechanical stress and degradation. Previous studies have shown that prolonged loading, such as running or marching, can deform the femoral cartilage and impact joint health.<sup>11</sup> The present study extends these findings to military cadets, suggesting that prolonged, repetitive loading may be associated with cartilage adaptation associated with limb asymmetry. Unlike sport-specific training, which is designed to optimize performance while minimizing injury risk, military training imposes prolonged and uncontrolled mechanical stress on the lower extremities. Activities such as long-distance marching, sprinting, and high-impact maneuvers introduce repetitive stressors that may contribute to localized cartilage thinning and asymmetric load distribution, as observed in the fail group.

lower limb asymmetry to better understand how repetitive loading influences joint health. The results indicated that cadets in the fail group exhibited significantly thinner femoral cartilage, particularly in the medial condyle of the right knee, as well as greater mediolateral cartilage thickness differences and knee flexion asymmetry at higher angular velocities. These findings indicate that prolonged and repetitive loading during military training may lead to structural and functional adaptations in the lower extremities.

Cartilage deformation is load-dependent. Previous studies have demonstrated that aerobic and resistance exercises reduce femoral cartilage thickness, although recovery occurs at different rates.<sup>14</sup> Specifically, recovery following aerobic exercise is slower than that following resistance training. The greater asymmetry observed in the fail group suggests that some cadets may have insufficient muscular adaptation to counteract prolonged mechanical loading. This aligns with findings that running and cycling can lead to cartilage thinning, whereas short-duration resistance exercises do not significantly alter cartilage thickness.<sup>6</sup> Continuous use of combat boots may further exacerbate lower extremity stress, reducing muscle elasticity and increasing the risk of injury.<sup>23</sup> Military training often involves extended aerobic exertion with intermittent high-impact activities, which may lead to cumulative joint stress in cadets with preexisting asymmetry or inadequate biomechanical adaptation. Over time, these factors may exacerbate existing structural imbalances.

Research comparing walking and drop landing has shown that high-impact loading conditions result in greater cartilage deformation and prolonged recovery times.<sup>13</sup> Although the cartilage typically recovers after unloading, excessive or repetitive asymmetric loading may result in nonlinear mechanical changes, affecting chondrocyte function, extracellular matrix integrity, and hydration balance. The increased mediolateral imbalance and flexion asymmetry observed in the fail group may reflect accumulated mechanical fatigue rather than a response to isolated training activities. The step-dependent cartilage deformation patterns observed in previous studies suggest that the cartilage exhibits a threshold response to prolonged loading, with nonlinear adaptations occurring beyond a critical workload.<sup>11</sup>

**Table 2. Comparison of medial and lateral femoral cartilage thickness between the pass and fail groups**

Variable		Medial	Lateral	<i>t</i>	<i>p</i>
Right	Pass group	1.63 ± 0.38	1.81 ± 0.27	1.538	0.072
	Fail group	1.39 ± 0.29	1.80 ± 0.34***	4.604	<0.001
Left	Pass group	1.49 ± 0.48	1.87 ± 0.27***	-3.495	0.001
	Fail group	1.36 ± 0.26	1.91 ± 0.37***	-4.871	<0.001

Values are expressed as mean ± SD, \*\*\* $p < 0.001$  by *t* test.

**Table 3. Factors influencing isokinetic knee strength based on G-test results**

Variable		Fail group	Fail group	F	t	p	
60°/s	Peak power (EX)	R	203.24 ± 25.17**	170.46 ± 30.78	1.008	3.213	0.002
		L	199.12 ± 27.63***	164.77 ± 24.34	1.755	3.549	0.001
	Peak power (FX)	R	112.41 ± 19.37	99.77 ± 22.14	0.019	1.665	0.054
		L	108.06 ± 21.90	106.62 ± 17.12	0.365	0.196	0.423
	Peak power/BW (EX)	R	279.47 ± 42.98*	247.23 ± 39.53	0.013	2.107	0.022
		L	271.41 ± 107.76	237.00 ± 21.48	3.803	1.130	0.134
	Peak power/BW (FX)	R	160.35 ± 29.98*	135.15 ± 26.10	0.499	2.410	0.011
		L	164.71 ± 66.58	150.23 ± 21.94	2.519	0.751	0.230
	Total work (EX)	R	614.29 ± 84.37***	500.38 ± 65.95	1.499	4.014	<0.001
		L	606.76 ± 101.26**	489.77 ± 108.02	0.124	3.047	0.002
	Total work (FX)	R	360.41 ± 72.03*	310.62 ± 55.98	0.501	2.059	0.024
		L	349.65 ± 67.50	339.62 ± 59.02	0.140	0.425	0.337
180°/s	Peak power (EX)	R	143.47 ± 122.00***	122.00 ± 22.09	0.027	3.511	0.001
		L	141.53 ± 22.09**	120.00 ± 16.05	0.678	2.962	0.003
	Peak power (FX)	R	80.82 ± 12.87*	72.23 ± 9.92	0.128	1.994	0.028
		L	80.06 ± 14.43	75.46 ± 11.11	1.118	0.952	0.175
	Peak power/BW (EX)	R	196.00 ± 172.31**	172.31 ± 19.75	0.308	2.783	0.005
		L	191.71 ± 19.02**	170.46 ± 21.80	0.594	2.846	0.004
	Peak power/BW (FX)	R	113.24 ± 14.86	102.23 ± 16.10	0.296	1.939	0.031
		L	111.24 ± 15.64	107.00 ± 18.29	0.187	0.683	0.250
	Total work (EX)	R	715.35 ± 125.25**	589.15 ± 101.43	0.239	2.962	0.003
		L	712.59 ± 119.36**	585.92 ± 119.07	0.144	2.883	0.004
	Total work (FX)	R	443.06 ± 63.05**	378.23 ± 72.19	0.271	2.622	0.007
		L	427.06 ± 75.24	415.38 ± 72.79	0.002	0.427	0.336
240°/s	Peak power (EX)	R	116.59 ± 9.91***	101.00 ± 10.17	0.115	4.220	<0.001
		L	114.41 ± 14.19***	97.38 ± 13.57	0.845	3.318	0.001
	Peak power (FX)	R	71.35 ± 9.23	70.15 ± 24.62	1.482	0.185	0.427
		L	71.94 ± 10.93	71.54 ± 9.54	0.339	0.106	0.458
	Peak power/BW (EX)	R	158.88 ± 16.93**	135.31 ± 28.89	1.614	2.802	0.005
		L	153.29 ± 21.06	148.23 ± 13.42	0.786	0.756	0.228
	Peak power/BW (FX)	R	97.18 ± 14.55	91.92 ± 14.38	0.078	0.985	0.167
		L	97.88 ± 17.26	102.62 ± 8.88	4.565	-0.899	0.188
	Total work (EX)	R	2,502.82 ± 281.19**	2,210.46 ± 27.16	0.006	2.870	0.004
		L	2,481.24 ± 283.58*	2,268.62 ± 391.76	2.609	1.726	0.048
	Total work (FX)	R	1,712.53 ± 261.35*	1,539.08 ± 248.68	0.061	1.839	0.038
		L	1,674.24 ± 284.85	1,693.08 ± 277.60	0.533	-0.181	0.429

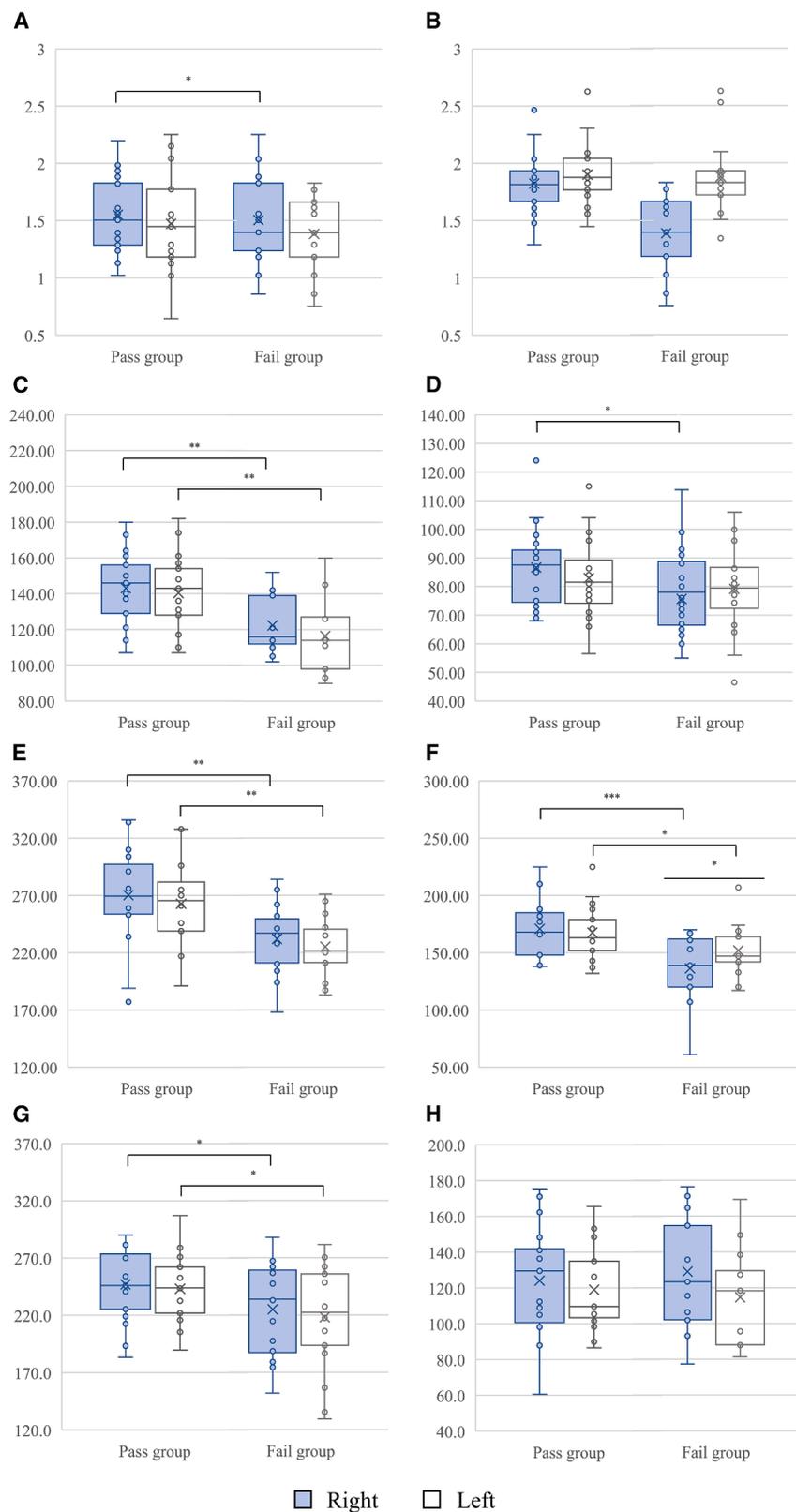
Values are expressed as mean ± SD, \* $p < 0.05$  by  $t$  test; BW, body weight; EX, extension; FX, flexion; R, right; L, left.

The observation that cartilage thickness initially decreases and then partially recovers at higher step counts highlights the importance of mechanical stress and recovery cycles in joint adaptation. However, cadets with greater limb asymmetry may have a reduced capacity to recover from repetitive loading, thereby increasing their risk of long-term musculoskeletal issues.

Although limb dominance and side preference were not measured in this study, it is plausible that habitual use of a dominant leg could lead to uneven stress accumulation between sides, contributing to the right-sided differences observed. This remains speculative but offers a potential explanation for the localized cartilage thinning. Future studies should include

limb dominance assessment to verify whether preferential use contributes to asymmetric mechanical loading and cartilage adaptation under high-intensity physical stress.

The pass group exhibited significantly greater lower limb muscle strength than did the fail group, in addition to differences in cartilage thickness. Lower limb muscle strength is essential for maintaining postural stability and generating force during movement. In aviation physiology, pilots strengthen their lower limb muscles to prevent G-LOC, which results from blood pooling in the lower extremities.<sup>24</sup> Previous studies have shown that individuals who completed 12 weeks of functional muscle training exhibited reduced muscle activation when exposed to high Gz



**Figure 2. Measurements of the left and right knees according to groups**

(A) medial condyle thickness; (B) lateral condyle thickness; (C) average power of the isokinetic knee strength extension test at 60°/s; (D) average power of the isokinetic knee strength flexion test at 60°/s; (E) average power of the isokinetic knee strength extension test at 180°/s; (F) average power of the isokinetic knee strength flexion test at 180°/s; (G) average power of the isokinetic knee strength extension test at 240°/s; and (H) average power of the isokinetic knee strength flexion test at 240°/s.

**Table 4. Knee strength asymmetry in the pass and fail groups based on isokinetic exercise testing**

Variable			Right	Left	t	p
60°/s	Peak power (EX)	Pass group	203.24 ± 25.17	199.12 ± 27.63	1.641	0.060
		Fail group	170.46 ± 30.78	164.77 ± 24.34	0.577	0.287
	Peak power (FX)	Pass group	112.41 ± 19.37	108.06 ± 21.90	0.963	0.175
		Fail group	99.77 ± 22.14	106.62 ± 17.12	-0.883	0.197
	Peak power/BW (EX)	Pass group	279.47 ± 42.98	271.41 ± 107.76	0.302	0.383
		Fail group	247.23 ± 39.53	237.00 ± 21.48	0.813	0.216
	Peak power/BW (FX)	Pass group	160.35 ± 29.98	164.71 ± 66.58	-0.341	0.369
		Fail group	135.15 ± 26.10	150.23 ± 21.94	-1.633	0.064
	Total work (EX)	Pass group	614.29 ± 84.37	500.38 ± 65.95	0.660	0.259
		Fail group	606.76 ± 101.26	489.77 ± 108.02	0.283	0.391
	Total work (FX)	Pass group	360.41 ± 72.03	349.65 ± 67.50	1.280	0.109
		Fail group	310.62 ± 55.98	339.62 ± 59.02	-1.383	0.096
180°/s	Peak power (EX)	Pass group	143.47 ± 122.00	141.53 ± 22.09	0.473	0.321
		Fail group	122.00 ± 22.09	120.00 ± 16.05	0.398	0.349
	Peak power (FX)	Pass group	80.82 ± 12.87	72.23 ± 9.92	0.255	0.401
		Fail group	75.46 ± 11.11	80.06 ± 14.43	-1.159	0.135
	Peak power/BW (EX)	Pass group	196.00 ± 172.31	191.71 ± 19.02	1.079	0.148
		Fail group	172.31 ± 19.75	170.46 ± 21.80	0.267	0.397
	Peak power/BW (FX)	Pass group	113.24 ± 14.86	111.24 ± 15.64	0.756	0.230
		Fail group	102.23 ± 16.10	107.00 ± 18.29	-1.285	0.112
	Total work (EX)	Pass group	715.35 ± 125.25	712.59 ± 119.36	0.234	0.409
		Fail group	589.15 ± 101.43	585.92 ± 119.07	0.090	0.465
	Total work (FX)	Pass group	443.06 ± 63.05	427.06 ± 75.24	1.514	0.075
		Fail group	378.23 ± 72.19*	415.38 ± 72.79	-2.352	0.018
240°/s	Peak power (EX)	Pass group	116.59 ± 9.91	114.41 ± 14.19	0.862	0.201
		Fail group	101.00 ± 10.17	97.38 ± 13.57	1.119	0.143
	Peak power (FX)	Pass group	71.35 ± 9.23	71.94 ± 10.93	-0.288	0.388
		Fail group	70.15 ± 24.62	71.54 ± 9.54	-0.166	0.435
	Peak power/BW (EX)	Pass group	158.88 ± 16.93*	153.29 ± 21.06	2.470	0.013
		Fail group	135.31 ± 28.89	148.23 ± 13.42	-1.519	0.077
	Peak power/BW (FX)	Pass group	97.18 ± 14.55	97.88 ± 17.26	-0.230	0.411
		Fail group	91.92 ± 14.38*	102.62 ± 8.88	-2.393	0.017
	Total work (EX)	Pass group	2,502.82 ± 281.19	2,481.24 ± 283.58	0.689	0.250
		Fail group	2,210.46 ± 27.16	2,268.62 ± 391.76	-0.635	0.269
	Total work (FX)	Pass group	1,712.53 ± 261.35	1,674.24 ± 284.85	1.228	0.119
		Fail group	1,539.08 ± 248.68*	1,693.08 ± 277.60	-1.920	0.039

Values are expressed as mean ± SD, \**p* < 0.05 by *t* test; BW, body weight; EX, extension; FX, flexion.

power, with corresponding reductions in physiological stress.<sup>24</sup> High muscle strength not only enhances resistance to gravitational acceleration but also supports the maintenance of symmetrical body function. Asymmetry in lower limb strength was more pronounced in the fail group, which also demonstrated greater differences in FMS scores, likely due to variations in core-supporting muscle strength.

These findings underscore the need for structured, individualized interventions in military populations. Unlike athletes who train with personalized programs to optimize performance and minimize injury, military training rarely accounts for individual biomechanical differences. Accordingly, periodic ultrasono-

graphic monitoring combined with targeted strength and neuromuscular control programs may help reduce asymmetry and improve long-term joint health.<sup>14</sup>

Although ultrasonography is a reliable, noninvasive tool for assessing cartilage thickness, it does not measure biomechanical properties such as stiffness or hydration, which are important for understanding cartilage adaptation. Furthermore, because this study included only male Air Force cadets from a single military academy, caution should be taken when generalizing the findings to other military populations, female personnel, or civilians engaged in different physical training environments. Nevertheless, ultrasonography has proven effective in detecting

acute cartilage changes in response to mechanical stress.<sup>11,13</sup> Although the present study focused on morphological assessment via ultrasonography, biochemical markers such as cartilage oligomeric matrix protein and type II collagen degradation products could provide additional insight into cartilage metabolism and mechanical stress responses. Future research integrating morphological and biochemical analyses would enhance understanding of load-induced cartilage adaptation. Future research should explore the long-term effects of military training on joint health and assess whether targeted interventions can improve cartilage resilience. As this study did not measure pre-training cartilage thickness, it remains unclear whether the observed asymmetry predated training or emerged as a result of repetitive physical stress. Future longitudinal studies are needed to determine the long-term effects of military training on cartilage adaptation.

### Limitations of the study

This study has several limitations. First, femoral cartilage morphology was assessed only with ultrasonography, which cannot capture cartilage biomechanical properties or biochemical markers of tissue turnover. Second, the relatively small sample of male fourth-year air force cadets from a single academy limits statistical power, reducing the ability to detect subtle between-group differences or evaluate higher-order interactions. This also restricts generalizability to other sexes, ages, or training environments. Third, the cross-sectional design lacked pre-training baseline measurements and longitudinal follow-up, making it unclear whether the observed asymmetries preceded or resulted from military training, or whether they are modifiable through targeted interventions. Finally, limb dominance and habitual unilateral loading were not directly quantified, which may have contributed to the observed side-to-side differences. Consequently, the practical recommendations drawn from these findings should be interpreted as preliminary and validated in future studies using larger, more diverse cohorts and longitudinal designs.

### Conclusions

This study suggests that the mechanical demands of military training may influence femoral cartilage morphology and lower limb function. Cadets exhibiting greater asymmetry were at a higher risk of musculoskeletal issues owing to joint instability and uneven load distribution. Similar patterns of cartilage adaptation have been observed in athletes subjected to repetitive limb asymmetry-related loading patterns, reinforcing the need for targeted interventions to address biomechanical imbalances. Implementing training strategies that promote symmetrical loading, combined with periodic musculoskeletal assessments, could enhance performance and reduce injury risk in military personnel. In particular, military physical training should prioritize symmetric hamstring strength and endurance during high-speed, functional movements to improve lower-limb kinetic symmetry and potentially reduce injury risk. Accordingly, future training programs should incorporate targeted strength and flexibility components to promote and maintain left-right symmetry. Strength programs should emphasize hamstring flexor balance and knee joint stability, as asymmetry at higher angular velocities

was evident in the fail group. Prospective work should test the efficacy of targeted strength training for cartilage resilience, investigate gait asymmetry and impact loading as biomechanical determinants of injury, and examine links between daily training volume and skeletal muscle mass. Understanding these mechanisms could inform personalized training programs aimed at minimizing asymmetry and enhancing joint stability in military populations.

### RESOURCE AVAILABILITY

#### Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Kyu-Lim Lee ([kyulimlee@yuhs.ac](mailto:kyulimlee@yuhs.ac)).

#### Materials availability

This study did not generate new unique reagents.

#### Data and code availability

- The dataset supporting the findings of this study is available from the corresponding author upon reasonable request.
- This study did not generate original code.
- No additional supporting items were generated.

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### AUTHOR CONTRIBUTIONS

All authors were well-informed of the WMA Declaration of Helsinki—Ethical Principles for Medical Research Involving Human Subjects—and confirmed that this study firmly fulfilled the declaration. None of the authors have financial or private relationships with commercial, academic, or political organizations or people that may have improperly influenced this research. 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 J.-Y.S.; data acquisition, analysis and interpretation, and major drafting and revision of manuscript submission were done by I.-K.K.; and overall organization and direct supervision of the research were undertaken by K.-L.L.

### DECLARATION OF INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

### STAR★METHODS

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## STAR★METHODS

## KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
<b>Biological samples</b>		
Human participants: Male Air Force cadets	Republic of Korea Air Force Academy	N/A
<b>Software and algorithms</b>		
Statistical software: SPSS	IBM Corp.	Version 26.0
Image analysis software: ImageJ	NIH	RRID: SCR_003070
<b>Deposited data</b>		
Raw ultrasound images & anonymized datasets	This study	Available upon request
<b>Other</b>		
Ultrasound device: SONON 500L (6–12 MHz)	Healcerion Co., Ltd., Seoul, Korea	500L
Isokinetic dynamometer (Cybex Humac Norm)	CSMi Medical Solutions	<a href="https://www.csmisolutions.com/humac-norm">https://www.csmisolutions.com/humac-norm</a>
Functional Movement Screen (FMS) Kit	Functional Movement Systems™, USA	N/A
G-test gravitational acceleration system	Republic of Korea Air Force Academy	N/A

## EXPERIMENTAL MODEL AND SUBJECT DETAILS

Participants were recruited over a two-week period beginning December 1, 2024, and all procedures, including measurement and data analysis, were completed prior to December 31, 2024. This study included 30 male fourth-year cadets from the Air Force Academy, the mean age of participants was 23.14 years. Upon entering the Air Force Academy, participants underwent standardized military training and regular physical education. Prior to admission (during high school), they reported no participation in organized sports beyond school-sponsored activities. Participants performed a G-test to investigate the effect of lateral asymmetry on +Gz resistance, and they were classified into the pass group ( $n = 17$ ) and the fail group ( $n = 13$ ) based on the G-test results. Participants were stratified solely by G-test outcome (Pass/Fail) because +Gz tolerance is the criterion construct of interest; training exposure was not used as a grouping or explanatory variable. Before participation, all cadets were informed of the study objectives, procedures, and potential risks and were advised of their right to withdraw at any time without consequences. Written informed consent was obtained from all participants. This study was approved by the Institutional Bioethics Committee of Gachon University (approval date: November 28, 2024; approval number: 1044396-202410-HR-169-01) and conducted under the principles of the Declaration of Helsinki.

## METHOD DETAILS

**Femoral cartilage thickness measurement**

Femoral cartilage thickness was measured using real-time two-dimensional B-mode ultrasonography (SONON 500 L; Healcerion Co., Ltd., Seoul, South Korea) with a high-frequency linear transducer. Participants were positioned with their backs supported and their dominant knee flexed to approximately  $140^\circ$ , verified using a manual goniometer. The transducer was placed transversely over the anterior knee and aligned with the medial and lateral femoral condyles, just above the superior border of the patella. Once the intercondylar notch was centered in the ultrasound image, and both femoral condyles were visible at the screen's lateral margins, three images were captured per knee (Figure 2). Cartilage thickness was measured at the midpoint of each condyle using ImageJ software (National Institutes of Health, Bethesda, MD, USA), with scale calibration based on image size. The final thickness was recorded as the mean of three independent measurements. All ultrasound assessments were performed by a single trained examiner to ensure intra-examiner reliability. Each site was imaged three times by a single trained examiner, and the mean value was used for analysis. Because the measurement variability was minimal, intraclass correlation coefficients (ICC) were not separately calculated in this dataset.

**Isokinetic strength testing**

Before testing, participants completed a questionnaire capturing dominant leg, primary use leg, injury history, injury duration, recovery status, pain presence, and pain intensity. Knee extensor and flexor strength were then assessed using an isokinetic dynamometer

(Cybex Humac Norm; Cybex International Corp., MA, USA). Participants performed a standardized warm-up consisting of light cycling and dynamic stretching. During testing, participants were seated with the hip flexed to 90°, the lower limbs supported and elevated, and the knee range of motion constrained between 0° (full extension) and 110° of flexion. The dynamometer performed automated gravity compensation and mechanical-axis alignment. To isolate knee action, stabilization was provided with straps across the thighs, pelvis/hips, and upper trunk/chest. Strength testing for knee extension and flexion was conducted at 60°/s (3 repetitions), 180°/s (5 repetitions), and 240°/s (26 repetitions); the 26 repetitions at 240°/s were selected to evaluate muscle endurance at high angular velocity, a condition relevant to high-intensity functional performance. A 60-s rest was provided between sets. Peak torque (N·m) and the hamstring-to-quadriceps (H/Q) ratio were recorded bilaterally. Standardized verbal encouragement was provided to elicit maximal effort on each trial.

### FMS evaluation

The FMS evaluation was conducted following standardized procedures by certified evaluators.<sup>25–27</sup> Before testing, participants were briefed on movement patterns and scoring criteria. The evaluation included seven movement patterns: deep overhead squat, hurdle step, inline lunge, trunk stability push-up, active straight leg raise, shoulder mobility, and rotary stability. Of these, five tests assessed bilateral symmetry. Each movement was scored on a 0–3 scale, where 0 indicated pain or inability to complete the movement, and 3 represented perfect execution. For each test, the final score was determined by the lowest recorded score for either side.

### G-test measurement

The G-test was conducted using a high-speed centrifuge gondola (ETC Corporate, Pennsylvania, USA) housed at the Air Force Aerospace Medical Center, Republic of Korea Air Force Academy. Participants were seated in a cockpit-style seat and exposed to 5 G acceleration for up to 30s. The gondola was initiated at 0.8 G and rapidly accelerated to 5 G once the participant engaged a lever. The test concluded after 30s, when the participant deactivated the lever, or if G-induced loss of consciousness (G-LOC) occurred. Participants were classified as pass if they completed the full 30s protocol without voluntary termination or loss of consciousness; all other outcomes were classified as fail.

## QUANTIFICATION AND STATISTICAL ANALYSIS

All variables satisfied the assumptions of normality, and there were no missing data points or dropouts in any of the measured variables. All statistical analyses were conducted using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Data are reported as means ± standard deviations. Variables entered into the analysis included body composition, FMS scores, isokinetic knee strength metrics (peak torque, average power, and total work for extension and flexion), and articular cartilage thickness in the medial and lateral compartments. Between-group differences were analyzed using independent t-tests and left–right asymmetry was analyzed using paired-samples 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. For sets of multiple comparisons, familywise error was controlled using the Bonferroni correction, with the adjusted significance level defined as  $\alpha_{adj} = 0.05/m$  within each family of tests. Statistical significance was set at  $p < 0.05$  or at the corresponding Bonferroni-adjusted threshold, as applicable.

## ADDITIONAL RESOURCES

This study is not a clinical trial and does not have a clinical trial registration number.