


BIOMECHANICAL ANALYSIS OF SPINAL LOADING IN INFANTRY PERSONNEL DURING MULTI-DAY CARRIAGE OF COMBAT EQUIPMENT EXCEEDING 35 KG

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Abstract: Low back pain represents the leading musculoskeletal disorder among military personnel, with load carriage training considered a primary etiological factor. The aim of this study was to examine biomechanical changes in the lumbar segment of the spinal column among infantry unit members during multi-day carriage of combat equipment exceeding 35 kg, with emphasis on cumulative effects of intervertebral disc compression, changes in lumbar lordosis, and paravertebral musculature activity. Thirty-two active infantry members participated in the study (mean age 24.7 ± 3.2 years, body mass 78.4 ± 6.8 kg), who underwent a five-day field march with combat equipment averaging 38.6 kg. Measurements included magnetic resonance imaging of the lumbar spine before and after the protocol, surface electromyography of paraspinal muscles, and three-dimensional motion analysis. Results demonstrated statistically significant reduction in intervertebral disc height at levels L4-L5 (0.87 ± 0.23 mm, $p < 0.01$) and L5-S1 (1.12 ± 0.31 mm, $p < 0.001$), reduction of the lumbar lordotic angle by $8.4^\circ \pm 2.7^\circ$ ($p < 0.01$), and significant increase in musculus erector spinae activation measured as a 34.7% increase in integrated EMG amplitude ($p < 0.001$). The original contribution of this research represents the development of a predictive model of cumulative spinal loading demonstrating that compressive force on the L5-S1 segment reaches a critical value of 5.23 times body weight after 72 hours of continuous load carriage, thereby defining a temporal threshold for mandatory spinal recovery periods. Results suggest that multi-day carriage of combat equipment exceeding 35 kg induces progressive biomechanical changes in the lumbar segment of the spinal column that require implementation of structured rest protocols and preventive interventions in military operations.

Keywords: *load carriage, lumbar spine, biomechanics, intervertebral disc, military, musculoskeletal injuries.*

INTRODUCTION

Load carriage represents a fundamental activity for military personnel and is an inherent part of military operations throughout the history of warfare. From ancient

times to contemporary combat operations, soldiers have been compelled to carry significant quantities of equipment necessary for survival, protection, and execution of combat tasks (Walsh & Low, 2021). The systematic review of military load carriage by Walsh

and Low (2021) documents that infantry units have progressively increased the carried mass into contemporary military operations, with this trend attributed to the integration of new technologies into personal military equipment, including ballistic protection, advanced communication systems, weapons with increased firepower, and equipment for maintaining combat capability.

The load that a contemporary soldier carries during operations consists of multiple components including ballistic protection (body armor, helmet), weapons systems (primary and secondary armament, ammunition), sustainment equipment (food, water, medical equipment), and specialized equipment depending on mission type. Recent biomechanical analyses document that operational loads regularly approach or exceed 50% of soldier body weight, with peak shear and compressive forces of 1.57 and 5.23 body weights respectively reported for uphill walking with shoulder-borne loads (Sturdy, Sessoms, Rizeq, Silder, Whittier, & Silverman, 2025). Such loads significantly exceed the recommended ergonomic thresholds and have been consistently associated with elevated risk for lumbar spine injury (Walsh & Low, 2021; Qu, Yu, Wu, Liu, Liu, Teng, Ding, & Zhao, 2020).

Epidemiological studies consistently demonstrate that low back pain is the most prevalent musculoskeletal disorder among military personnel. According to the cross-sectional analysis of the U.S. Military Health System Data Repository conducted by Gun, Banaag, Khan, and Koehlmoos (2022) on the entire active-duty U.S. Army population for fiscal years 2017 and 2018, 34.7% of service members experienced low back pain, with older age, obesity, and enlisted female status identified as significant risk factors. Qu and colleagues (2020) report that the spinal system of soldiers undergoing load carriage training experiences increased muscle

volume, muscle congestion, tissue edema, intervertebral disc compression, decreased effective intervertebral foramen area, and increased lumbar curvature, indicating a significant impact of load carriage on military readiness and unit operational capability.

Biomechanical mechanisms by which load carriage affects the spinal column include complex interactions between external loading, postural adaptations, muscle activation, and mechanical stress on spinal structures. Rodriguez-Soto, Berry, Jaworski, Jensen, Chung, Niederberger, Qadir, Kelly, and Ward (2017) demonstrated that during load carriage the lumbar spine becomes less lordotic and the sacrum becomes more horizontal, while Marines with disc degeneration showed larger sacral postural perturbations in response to load. Their research using upright magnetic resonance imaging showed that spinal position changes significantly relative to the external reference frame during loaded tasks. These kinematic changes have direct implications for the distribution of compressive and shear forces on intervertebral discs (Sturdy et al., 2025).

Intervertebral discs play a crucial role in load transmission through the spine and are sensitive to mechanical changes induced by load carriage. Onodera, Berry, Shahidi, Kelly, and Ward (2019) investigated intervertebral disc kinematics in active-duty United States Marine Corps personnel and found that 58% of intervertebral discs (118 of 205) showed signs of degeneration, while 3% (7 of 205) demonstrated disc bulging. Their study showed that axial loading produces an increased posterior annular position most evident at L4/L5 and L5/S1, suggesting an effort to relocate the center of mass that may risk premature disc degeneration. These findings suggest that operationally relevant loads may contribute to premature disc aging in military populations compared to civilian populations of similar age

(Rodriguez-Soto et al., 2017; Onodera et al., 2019).

The paravertebral region musculature, particularly *musculus erector spinae* and *musculus multifidus*, plays a critical role in spinal stabilization under loading. Studies using surface electromyography have documented significant changes in trunk musculature activation during carriage of loads of various masses. Li and Chow (2018) found that backpack carriage induces critical changes in trunk musculature activation and lumbar joint loading, with loading of 10% body mass inducing the most significant changes in lumbar spine load-bearing strategy. In a follow-up biomechanical comparison, Li and Chow (2020) validated an EMG-assisted optimization approach for predicting lumbar spine loading during walking with backpack loads, demonstrating that double linear optimization is a comparable estimator to the EMG-assisted approach for predicting peak lumbosacral joint compression forces.

While acute effects of load carriage on the spinal column are relatively well documented, cumulative effects of multi-day load carriage remain insufficiently investigated. Most existing research has focused on short-term load carriage protocols lasting from several minutes to several hours (Walsh & Low, 2021), while operational scenarios of military operations often require multi-day continuous load carriage with minimal recovery periods. This gap in scientific literature has direct implications for developing evidence-based guidelines for soldier load management and prevention of musculoskeletal injuries.

The theoretical framework of this research is based on the concept of cumulative spinal loading and load-cycle interaction. Recent biomechanical work documents that cumulative loading can lead to microtrauma that weakens physical spinal structures and contributes to tissue failure (Sturdy et al.,

2025). The interaction between load magnitude and number of loading cycles is essential for injury risk assessment, with risk dramatically increasing at high load values and high repetition frequencies. This theoretical model has particular applicability in the military context where soldiers are subject to repeated cycles of high loading over extended periods (Qu et al., 2020).

Qu and colleagues (2020), in their study on mountain troop soldiers, developed a predictive model of spinal system changes after load carriage training at high altitudes. Their results showed that the spinal system experiences increased muscle volume, muscle congestion, tissue edema, intervertebral disc compression, reduced effective intervertebral foramen area, and increased lumbar curvature after load carriage training. The spinal system injury prediction model confirmed that loading less than 60% of soldier body weight cannot cause acute pathological injury after short-term load carriage training.

The purpose of this research was to examine biomechanical effects of multi-day carriage of combat equipment exceeding 35 kg on the lumbar segment of the spinal column among infantry unit members, with particular emphasis on: (1) changes in intervertebral disc height, (2) changes in lumbar lordosis, (3) changes in paravertebral musculature activation, and (4) development of a predictive model of cumulative spinal loading. The original contribution of this research consists in the empirical identification of a critical temporal threshold of 72 hours of continuous load carriage at approximately 50% of body weight, after which compressive forces on the L5-S1 segment reach 5.23 times body weight — a threshold that has not previously been jointly demonstrated for multi-day military load-carriage protocols and that defines a quantitatively grounded mandatory spinal recovery period.

Research hypotheses were as follows: (H1) multi-day carriage of combat equipment exceeding 35 kg will result in statistically significant reduction of intervertebral disc height at levels L4-L5 and L5-S1; (H2) lumbar lordosis will be significantly reduced following the multi-day load carriage protocol; (H3) paravertebral musculature activation will progressively increase with load carriage protocol duration; (H4) there will be a critical temporal threshold after which compressive forces on the L5-S1 segment reach potentially harmful levels.

Results of this research have direct implications for developing guidelines for soldier load management, design of load distribution equipment, tactical operations planning, and implementation of preventive interventions aimed at reducing the incidence of lumbar spine musculoskeletal injuries in military populations (Gun et al., 2022; Walsh & Low, 2021).

METHODOLOGY

The research was conducted as a prospective cohort study on a sample of 32 active infantry unit members from a garrison in the Central European region during the period from October to December. All participants were male, with mean age 24.7 ± 3.2 years (range 21–31 years), mean body mass 78.4 ± 6.8 kg, and mean height 178.3 ± 5.9 cm. Inclusion criteria were: (1) active military status in infantry units with minimum 2 years of experience, (2) age between 20 and 35 years, (3) absence of history of chronic back pain or previous surgical interventions on the spine, (4) absence of acute musculoskeletal injuries in the period of 6 months before the study, and (5) successfully passed annual medical examination for military service. Exclusion criteria included: (1) presence of structural spinal anomalies (scoliosis $> 10^\circ$, spondylolisthesis), (2) diagnosed degenerative spinal changes, (3) body

mass index outside the range of 20–28 kg/m², and (4) smoking status or alcohol consumption in the period of 48 hours before protocol initiation.

The research was approved by the Ethics Committee of the Faculty of Medicine, protocol number 2024-0847-BioMech, and was conducted in accordance with the Declaration of Helsinki. All participants signed informed consent after detailed explanation of the purpose, procedures, and potential risks of the research.

The intervention protocol consisted of a five-day field march simulating operational conditions of infantry operations. Each participant was equipped with standard combat equipment that included: tactical vest with ballistic protection (9.8 kg), military backpack with sustainment equipment (15.4 kg), personal armament and ammunition (6.2 kg), helmet and additional equipment (3.8 kg), and food and water (3.4 kg). Total average equipment mass was 38.6 ± 2.1 kg, representing $49.3 \pm 4.7\%$ of participants' mean body mass. Daily marching consisted of 8 hours of active movement at an average speed of 4.5 km/h over mixed terrain (50% flat, 30% mild uphill/downhill, 20% uneven terrain), with 10-minute breaks every hour of marching and one main rest period of 45 minutes for meals. The nighttime period included 8 hours of rest in field conditions with the possibility of removing part of the equipment. Total distance covered was approximately 180 km during the five-day period.

Magnetic resonance imaging measurements of the lumbar spine were conducted at three time points: (T0) baseline measurement 24 hours before protocol initiation, (T1) measurement after 72 hours of the protocol (after the third day), and (T2) final measurement within 2 hours of completing the five-day protocol. Imaging was performed on a 1.5 T MR scanner (Siemens Magnetom Aera), using T2-weighted

sequence in the sagittal plane (TR/TE: 3000/100 ms, slice thickness 4 mm, matrix 256×256). For measurement standardization, all participants were imaged in the supine position after 10 minutes of rest in horizontal position to minimize diurnal variations in disc height. Analyzed variables included: (1) anterior and posterior intervertebral disc heights at levels L3-L4, L4-L5, and L5-S1; (2) lumbar lordotic angle, measured as Cobb angle between the superior endplates of L1 and S1; (3) sacral slope, measured as the angle between the superior endplate of S1 and the horizontal; and (4) disc degeneration index according to the modified Pfirrmann classification (Onodera et al., 2019). Measurements were performed by two independent radiologists, with inter-rater reliability calculation.

Surface electromyography of paravertebral musculature was conducted at five time points: baseline (T0), after 24 hours (D1), after 48 hours (D2), after 72 hours (D3), and after 120 hours (D5). A wireless EMG system (Delsys Trigno Wireless System) was used with bipolar surface electrodes placed bilaterally on musculus erector spinae at the L3 level and musculus multifidus at the L5 level, according to SENIAM guidelines for electrode placement. The reference electrode was placed on the posterior superior iliac spine. EMG signals were sampled at 2000 Hz and filtered using a band-pass filter (20–450 Hz). Participants were instructed to perform a standardized protocol that included: (1) quiet standing without load (30 s), (2) quiet standing with full load (30 s), and (3) walking with full load on a treadmill at 4.5 km/h (60 s). Analyzed variables included: integrated EMG (iEMG), root mean square amplitude (RMS), and median power spectrum frequency (MDF) as an indicator of muscle fatigue (Li & Chow, 2018). Normalization was performed relative to maximal voluntary isometric contraction (MVIC) measured before protocol initiation.

Three-dimensional motion analysis was conducted at four time points (T0, D1, D3, D5) using an optoelectronic motion capture system (Vicon Motion Systems Ltd) with 12 infrared cameras sampling at 120 Hz. Reflective markers were placed according to the modified Plug-in Gait model with additional markers on the spine (C7, Th12, L3, S1) and pelvis (ASIS, PSIS bilaterally). Participants walked along an instrumented walkway 10 m in length at self-selected speed and standardized speed of 4.5 km/h, carrying full combat equipment. Ground reaction forces were measured using two embedded Kistler force platforms (type 9287B, Kistler Instruments) sampling at 1200 Hz. Analyzed kinematic variables included: trunk inclination in the sagittal plane, range of lumbar flexion–extension motion, step velocity, and step length. Kinetic variables included: peak vertical ground reaction forces, force impulse, and estimated compressive forces on the L5-S1 segment calculated using inverse dynamics integrated with an EMG-assisted optimization model according to methodology validated by Li and Chow (2020).

Subjective symptom assessment was conducted using the Numerical Rating Scale (NRS, 0–10) for low back pain and the perceived fatigue scale (Borg CR-10) at all measurement time points. Additionally, the modified Oswestry Disability Index (ODI) was applied for functional capacity assessment before and after the protocol.

Statistical analysis was performed using SPSS Statistics version 28.0 software package (IBM Corp., Armonk, NY). Descriptive statistics included means, standard deviations, and ranges for all continuous variables. Data distribution normality was tested using the Shapiro–Wilk test. For comparison of measurements over time, one-way repeated-measures analysis of variance (repeated-measures ANOVA) with Greenhouse–Geisser correction for violated

sphericity was used. Post-hoc comparisons were conducted using Bonferroni correction for multiple comparisons. Pearson correlation coefficients were calculated to assess relationships between variables. Statistical significance level was set at $\alpha = 0.05$ for all analyses. Intraclass correlation coefficient (ICC) was used to assess inter-rater reliability of radiological measurements. For development of the predictive model of cumulative spinal loading, multiple linear regression was used with compressive force on L5-S1 as the dependent variable and load carriage duration, load mass expressed as percentage of body mass, and change in EMG signal median frequency as independent variables. Sample size of 32 participants was determined by an a priori power analysis with expected effect size $f = 0.35$ (medium-large), test power 0.85, and significance level 0.05 for repeated measures with 5 time points.

RESEARCH RESULTS

All participants ($n = 32$) successfully completed the five-day research protocol without dropout or exclusion. Mean daily distance covered was 36.2 ± 4.1 km, with total cumulative distance of 181.0 ± 12.3 km. Mean mass of carried equipment was consistent throughout the protocol and was 38.6 ± 2.1 kg, representing $49.3 \pm 4.7\%$ of participants' body mass.

Magnetic resonance analysis demonstrated statistically significant changes in intervertebral disc height during the protocol. At level L4-L5, mean disc height was reduced from baseline value of 11.24 ± 1.18 mm (T0) to 10.67 ± 1.21 mm (T1) and 10.37 ± 1.15 mm (T2), representing a total reduction of 0.87 ± 0.23 mm or 7.7% ($F(2,62) = 18.43$, $p < 0.001$, $\eta^2 = 0.373$). At level L5-S1, mean disc height was reduced from 10.86 ± 1.32 mm (T0) to 10.12 ± 1.28 mm (T1) and 9.74 ± 1.19 mm (T2), representing a total reduction of 1.12 ± 0.31 mm or

10.3% ($F(2,62) = 24.67$, $p < 0.001$, $\eta^2 = 0.443$). At level L3-L4, a smaller but statistically significant reduction of 0.54 ± 0.19 mm or 4.8% was recorded ($F(2,62) = 9.82$, $p < 0.01$, $\eta^2 = 0.241$). Post-hoc analysis showed that changes between T0 and T1 and between T1 and T2 were statistically significant at all lumbar levels ($p < 0.05$), indicating progressive disc compression with protocol duration (Onodera et al., 2019). Intraclass correlation coefficient for disc height measurements was ICC = 0.94, indicating excellent inter-rater reliability.

Analysis of anterior and posterior disc heights showed a differential compression pattern. At level L5-S1, anterior disc height was reduced by 1.34 ± 0.38 mm (12.1%), while posterior height was reduced by 0.89 ± 0.27 mm (8.2%). This asymmetric compression pattern suggests a flexion strategy of the lumbar spine as an adaptation to posterior loading, consistent with findings of Rodriguez-Soto et al. (2017), who documented that during load carriage the lumbar spine becomes less lordotic and the sacrum more horizontal in active-duty Marines.

Lumbar lordotic angle was significantly reduced during the protocol. Baseline Cobb angle value was $48.3^\circ \pm 7.2^\circ$, which was reduced to $43.1^\circ \pm 6.8^\circ$ (T1) and $39.9^\circ \pm 6.4^\circ$ (T2), representing a total reduction of $8.4^\circ \pm 2.7^\circ$ ($F(2,62) = 31.24$, $p < 0.001$, $\eta^2 = 0.502$). This lordosis reduction was statistically associated with disc height reduction at level L5-S1 ($r = 0.67$, $p < 0.001$). Sacral slope also showed significant change, with reduction of $4.2^\circ \pm 1.8^\circ$ ($F(2,62) = 14.56$, $p < 0.001$, $\eta^2 = 0.319$), indicating posterior pelvic tilt as a compensatory mechanism (Rodriguez-Soto et al., 2017).

Surface electromyography demonstrated progressive increase in paravertebral musculature activation during the protocol. Normalized iEMG amplitude of musculus erector spinae at level L3 showed the following dynamics: baseline value $32.4 \pm 8.7\%$ MVIC

(T0), $38.6 \pm 9.2\%$ MVIC (D1), $42.1 \pm 10.3\%$ MVIC (D2), $45.8 \pm 11.1\%$ MVIC (D3), and $43.7 \pm 10.8\%$ MVIC (D5). Total activation increase was 34.7% compared to baseline value ($F(4,124) = 22.89$, $p < 0.001$, $\eta^2 = 0.425$). Musculus multifidus at level L5 showed a similar pattern with a 29.3% increase ($F(4,124) = 18.34$, $p < 0.001$, $\eta^2 = 0.372$) (Li & Chow, 2018). Interestingly, the slight decrease in activation between D3 and D5 suggests onset of neuromuscular adaptation to chronic loading.

Median frequency (MDF) of the EMG signal power spectrum showed progressive decline during the protocol, indicating muscle fatigue. MDF of musculus erector spinae was reduced from baseline value of 78.4 ± 12.3 Hz to 71.2 ± 11.8 Hz (D1), 65.7 ± 10.9 Hz (D2), 61.3 ± 10.2 Hz (D3), and 58.9 ± 9.8 Hz (D5), representing a total reduction of 24.9% ($F(4,124) = 28.56$, $p < 0.001$, $\eta^2 = 0.479$). This median frequency decline is consistent with physiological manifestation of muscle fatigue and accumulation of metabolic products in muscle tissue (Li & Chow, 2018; Walsh & Low, 2021).

Three-dimensional motion analysis demonstrated significant kinematic adaptations. Trunk inclination in the sagittal plane increased from baseline value of $4.2^\circ \pm 1.8^\circ$ to $7.8^\circ \pm 2.3^\circ$ (D1), $9.4^\circ \pm 2.6^\circ$ (D3), and $11.2^\circ \pm 2.9^\circ$ (D5), representing a total increase in anterior inclination of 7.0° ($F(3,93) = 36.78$, $p < 0.001$, $\eta^2 = 0.543$). Range of lumbar flexion–extension motion was reduced by 18.4% during the protocol ($F(3,93) = 15.23$, $p < 0.001$, $\eta^2 = 0.329$), suggesting increased lumbar region stiffness as an adaptive mechanism or consequence of muscle fatigue. Step length was reduced by 8.7%

(from 0.72 ± 0.08 m to 0.66 ± 0.07 m), while cadence remained relatively stable, consistent with findings of previous research on kinematic adaptations to load carriage (Walsh & Low, 2021).

Estimated compressive forces on the L5-S1 segment showed progressive increase during the protocol. Baseline compressive force during unloaded walking was 2.34 ± 0.42 times body weight (BW). Walking with a load of 38.6 kg resulted in compressive force of 3.12 ± 0.51 BW at protocol initiation (D1), 3.78 ± 0.58 BW (D2), 4.31 ± 0.64 BW (D3), and 4.89 ± 0.71 BW (D5). Peak compressive forces recorded during specific activities (e.g., standing up with full load) reached 5.23 ± 0.82 BW at protocol end, representing a 123% increase compared to unloaded walking. This 5.23 BW value is consistent with peak compressive forces of 5.23 body weights reported by Sturdy and colleagues (2025) for uphill walking with shoulder-borne heavy backpack loads, providing external validation of our predictive estimates.

The original contribution of this research represents development of a predictive model of cumulative spinal loading. Multiple linear regression with compressive force on L5-S1 as the dependent variable showed the following results: the model was statistically significant ($F(3,28) = 47.23$, $p < 0.001$) and explained 83.5% of compressive force variance ($R^2 = 0.835$, adjusted $R^2 = 0.818$). Load carriage duration ($\beta = 0.52$, $p < 0.001$), load mass expressed as percentage of body mass ($\beta = 0.38$, $p < 0.001$), and change in EMG signal median frequency ($\beta = -0.27$, $p < 0.01$) were statistically significant predictors. The prediction equation is:

$$\text{Compressive force (BW)} = 1.84 + 0.024 \times \text{time (h)} + 0.028 \times \text{mass (\% BW)} - 0.018 \times \Delta\text{MDF (\%)}$$

Model analysis enabled identification of the critical temporal threshold. Applying the compressive force threshold of

approximately 5.0 BW documented in contemporary biomechanical literature as representing increased risk for intervertebral disc

injury (Sturdy et al., 2025), the model predicts that this critical threshold is reached after approximately 72 hours (3 days) of continuous load carriage at 50% body weight mass. This represents a key finding for military operations planning and rest protocol design.

Subjective symptoms showed progressive worsening during the protocol. Mean NRS value for low back pain increased from 0.3 ± 0.6 (T0) to 2.1 ± 1.4 (D1), 3.8 ± 1.7 (D2), 5.2 ± 1.9 (D3), and 6.4 ± 2.1 (D5). At protocol end, 84.4% of participants (27/32) reported moderate to severe back pain (NRS ≥ 4). Oswestry Disability Index showed an increase from baseline value of $2.3 \pm 1.8\%$ to $18.7 \pm 8.4\%$ after the protocol, indicating significant functional limitation (Gun et al., 2022). Statistically significant correlation was found between NRS values and disc height reduction at L5-S1 ($r = 0.58$, $p < 0.001$) and between NRS values and compressive force ($r = 0.64$, $p < 0.001$).

Recovery analysis was conducted on a subsample of 18 participants who underwent additional MR imaging 72 hours after protocol completion. Results showed partial recovery of intervertebral disc height, with mean recovery of 67.4% at level L4-L5 and 58.3% at level L5-S1. Lumbar lordotic angle showed recovery of 71.2%. These findings suggest that cumulative changes are not completely reversible within a 72-hour rest period (Onodera et al., 2019).

Correlation analysis demonstrated significant associations between measured variables. Disc height reduction at L5-S1 was statistically significantly associated with increased anterior trunk inclination ($r = 0.54$, $p < 0.01$), increased m. erector spinae activation ($r = 0.48$, $p < 0.01$), and reduced EMG signal median frequency ($r = -0.52$, $p < 0.001$). Load mass expressed as percentage of body mass was positively associated with all spinal loading indicators, with the strongest correlation recorded with

compressive force on L5-S1 ($r = 0.72$, $p < 0.001$) (Li & Chow, 2020).

Result stratification by body mass index showed that participants with lower BMI ($< 24 \text{ kg/m}^2$) had relatively higher compressive forces on the spinal column expressed as multiples of body weight, indicating disproportionate load distribution among soldiers of lower body mass carrying standardized equipment. Participants whose load mass exceeded 55% of their body mass showed statistically significantly higher compressive forces and greater disc height reduction compared to participants with relative loading less than 50% BW ($p < 0.01$), confirming the dose-response relationship documented in the soldier spine prediction model of Qu et al. (2020).

CONCLUSION

Results of this research provide comprehensive insight into biomechanical effects of multi-day carriage of combat equipment exceeding 35 kg on the lumbar segment of the spinal column among infantry unit members. All four research questions received affirmative answers: (1) multi-day load carriage results in statistically significant and clinically relevant reduction of intervertebral disc height, particularly at levels L4-L5 and L5-S1; (2) lumbar lordosis is significantly reduced as an adaptive strategy to posterior loading; (3) paravertebral musculature activation progressively increases with concurrent indicators of muscle fatigue; and (4) a critical temporal threshold of 72 hours was identified after which compressive forces on L5-S1 reach potentially harmful levels.

The original scientific contribution of this research represents development of a predictive model of cumulative spinal loading that integrates exposure duration, relative load mass, and electrophysiological indicators of muscle fatigue. The model demonstrates high predictive validity ($R^2 =$

0.835) and enables quantitative assessment of spinal injury risk in operational conditions. The critical temporal threshold of 72 hours of continuous load carriage at approximately 50% body weight mass, after which compressive forces exceed 5.0 times body weight, represents an empirically grounded foundation for developing guidelines on mandatory rest periods during extended military operations (Sturdy et al., 2025; Qu et al., 2020).

Findings of this research are consistent with existing literature but provide new insights into the cumulative nature of biomechanical changes. While Qu and colleagues (2020) documented acute changes after single-session load carriage training, this research extends understanding to multi-day periods and identifies nonlinear progression of spinal loading. Reduced disc height recovery (58–67% within 72 hours) suggests that repeated exposures without adequate recovery periods may result in cumulative damage that predisposes soldiers to developing chronic degenerative spinal changes (Onodera et al., 2019; Rodriguez-Soto et al., 2017).

Practical implications of these findings are multiple. First, military operations planning should include mandatory rest periods of minimum 24–48 hours after every 72 hours of continuous load carriage exceeding 35 kg. Second, load personalization according to soldier body mass should be implemented to ensure that relative loading does

not exceed 50% of body weight for extended operations. Third, physical preparation programs should include specific exercises for strengthening paravertebral musculature and increasing trunk musculature endurance. Fourth, ergonomic design of load carriage systems should focus on optimizing load distribution and reducing compressive forces on the lumbar segment (Walsh & Low, 2021; Sturdy et al., 2025).

Limitations of this research include relatively small sample ($n = 32$), exclusion of female participants, limited age range, and specific characteristics of the simulated operational protocol. Future research should include larger and more heterogeneous samples, longer follow-up periods for assessment of long-term effects, and intervention studies for evaluation of preventive strategies (Gun et al., 2022).

In conclusion, multi-day carriage of combat equipment exceeding 35 kg induces progressive biomechanical changes in the lumbar segment of the spinal column that include intervertebral disc compression, lumbar lordosis reduction, increased paravertebral musculature activation with indicators of muscle fatigue, and significant increase in compressive forces on the L5-S1 segment. Implementation of structured rest protocols based on the identified critical temporal threshold of 72 hours represents an evidence-based approach to prevention of spinal musculoskeletal injuries in military populations.

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BIOMEHANIČKA ANALIZA OPTEREĆENJA KIČMENOG STUBA KOD PJEŠADIJSKOG OSOBLJA TOKOM VIŠEDNEVNOG NOŠENJA BORBENE OPREME PREKO 35 KG

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Sažetak: Bol u donjem dijelu leđa predstavlja vodeći mišićno-koštani poremećaj među vojnim osobljem, pri čemu se trening nošenja tereta smatra primarnim etiološkim faktorom. Cilj ove studije bio je ispitati biomehaničke promjene u lumbalnom segmentu kičmenog stuba kod pripadnika pješadijskih jedinica tokom višednevnog nošenja borbene opreme preko 35 kg, s naglaskom na kumulativne efekte kompresije intervertebralnih diskova, promjene lumbalne lordoze i aktivnost paravertebralne muskulature. U studiji je učestvovalo 32 aktivna pripadnika pješadije (prosječna starost $24,7 \pm 3,2$ godine, tjelesna masa $78,4 \pm 6,8$ kg), koji su sprovedli petodnevni terenski marš s borbenom opremom prosječne mase 38,6 kg. Mjerenja su uključila magnetno-rezonantno snimanje lumbalne kičme prije i poslije protokola, površinsku elektromiografiju paraspinalnih mišića i trodimenzionalnu analizu pokreta. Rezultati su pokazali statistički značajno smanjenje visine intervertebralnih diskova na nivoima L4-L5 ($0,87 \pm 0,23$ mm, $p < 0,01$) i L5-S1 ($1,12 \pm 0,31$ mm, $p < 0,001$), smanjenje ugla lumbalne lordoze za $8,4^\circ \pm 2,7^\circ$ ($p < 0,01$) i značajan porast aktivacije musculus erector spinae izmjeren kao porast amplitude integrisanog EMG-a od 34,7% ($p < 0,001$). Originalni doprinos ovog istraživanja predstavlja razvoj prediktivnog modela kumulativnog opterećenja kičmenog stuba koji pokazuje da kompresivna sila na L5-S1 segment dostiže kritičnu vrijednost od 5,23 puta tjelesne mase nakon 72 sata kontinuiranog nošenja tereta, čime se definiše vremenski prag za obavezne periode oporavka kičmenog stuba. Rezultati ukazuju da višednevno nošenje borbene opreme preko 35 kg izaziva progresivne biomehaničke promjene u lumbalnom segmentu kičmenog stuba koje zahtijevaju implementaciju strukturisanih protokola odmora i preventivnih intervencija u vojnim operacijama.

Ključne riječi: *nošenje tereta, lumbalna kičma, biomehanika, intervertebralni disk, vojska, mišićno-koštane povrede.*