



The Role of Boot Material and Accumulated Wear on Ankle Joint Co-Contraction During Running: A Six-Month Longitudinal Study

Milad Piran Hamlabadi ^{1,*}

¹ Department of Sport Sciences, Faculty of Humanities and Social Sciences, University of Ardakan, Ardakan, Iran

***Corresponding Author:** Department of Sport Sciences, Faculty of Humanities and Social Sciences, University of Ardakan, Ardakan, Iran. Email: miladpiran@ardakan.ac.ir

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Abstract

Background: The cumulative distance run in a given pair of running shoes is a primary determinant of a runner's susceptibility to injury.

Objectives: This study examined how accumulated mileage in military footwear affects ankle muscle co-contraction patterns during running.

Methods: Fifteen healthy men each received three new pairs of combat boots made from different materials: rubber, thermoplastic polyurethane, and polyurethane (PU). Participants wore the boots regularly for 6 months. Before and after this period, surface electromyography (EMG) signals were recorded while participants ran at a fixed speed of 3.2 m/s. Ankle muscle co-contraction indices were calculated from these recordings. Data were analyzed using a two-way repeated-measures analysis of variance.

Results: No significant changes were observed in general ankle co-contraction. Directed co-contraction during push-off showed a significant effect ($P = 0.046$, $\eta^2p = 0.125$). Subsequent paired comparisons showed that PU boots elicited significantly greater co-contraction during push-off than rubber boots. A significant effect was also observed for directed ankle co-contraction during the loading response phase ($P = 0.011$, $\eta^2p = 0.282$).

Conclusions: Different boot types may influence ankle co-contraction patterns during specific phases of running. These findings underscore the importance of considering boot type and measurement time points when assessing ankle muscle activity during physical activity.

Keywords: Ankle Co-contraction, Military Footwear, Rubber, Thermoplastic Polyurethane, Polyurethane

1. Background

Lower limb injuries during walking are highly prevalent among physically active individuals, with a two-year incidence of 66% (73% in women and 62% in men) (1). To date, 28 distinct lower limb injuries have been documented in association with running, including shin splints, Achilles tendinopathy, heel pain, knee pain, ankle sprains, iliotibial band syndrome, hamstring strains, stress fractures, and patellofemoral pain (2). Repetitive microtrauma to the musculoskeletal system and adverse biomechanical factors are considered early risk factors for running-related injuries (2).

As the primary interface between the foot and the ground, footwear plays a critical role in gait biomechanics and is an important consideration in the management and prevention of lower limb injuries (3). Boots are widely used in rehabilitation, sports, and occupational settings to support and protect the foot and ankle on uneven terrain and under diverse weather conditions. However, compared with conventional athletic shoes, boots typically have limited flexibility, inferior cushioning, and greater mass. These characteristics have been associated with altered gait biomechanics and an increased risk of lower limb injuries. The shaft height and stiffness of military footwear restrict the natural mobility of the ankle-foot complex during walking, running, and stair climbing. This restriction may

alter kinetic parameters during gait and necessitate compensatory adjustments at proximal joints, thereby changing muscle loading patterns and potentially increasing the risk of musculoskeletal injuries. Sinclair et al. reported that walking in boots increases patellofemoral joint stress (4), Achilles tendon loading (5), and impact parameters (6), while also increasing foot inversion and tibial external rotation (6). These biomechanical deviations have been closely linked to the etiology of running-related injuries.

Military boots have frequently been identified as a contributing factor to the high injury rates among military recruits (7), partly because of their limited capacity to attenuate vertical impact loading. Epidemiological evidence suggests a positive correlation between impact shock magnitude and the development of chronic injuries (8). This association may reflect the fact that military boots are primarily designed for protection, traction, and prevention of ankle inversion sprains rather than for shock absorption (9). Repetitive loading has also been shown to increase the likelihood of chronic running injuries (8).

Muscle co-contraction is the simultaneous activation of agonist and antagonist muscles surrounding a joint (10). Increased co-contraction during walking can increase metabolic energy expenditure and muscle fatigue, thereby increasing the overall metabolic cost of locomotion (11). Despite the established importance of muscle co-contraction in joint stability and injury risk, data on lower extremity muscle coordination during running in worn versus new footwear remain limited.

2. Objectives

This study examined how accumulated mileage in military footwear affects ankle muscle co-contraction patterns during running.

3. Methods

The study used a double-blind, repeated-measures design, with all participants completing every experimental condition.

3.1. Participants

An a priori power calculation was performed using G*Power. A one-sided calculation was specified using the F-test family and the repeated-measures analysis of variance (ANOVA) within-between interaction test (12). The power analysis indicated that a minimum sample of 15 participants was required to detect large interaction effects for kinetic outcomes. A total of 15 healthy male soldiers (age: 22.3 ± 1.7 years; height: 162.3 ± 6.5 cm; mass: 62.4 ± 9.3 kg) met the inclusion criteria and were enrolled. All

participants were physically active soldiers with at least 365 days of experience in recreational training, including walking and/or running three times per week for 50 min per session. All participants were right-footed and had previous experience with the boot model used in this study. Exclusion criteria included previous musculoskeletal surgery of the trunk or lower limbs and any neuromuscular or orthopedic conditions. The study was approved by the Ethics Committee of Mohaghegh Ardabili University (IR.UMA.REC.1401.026) and the Iranian Registry of Clinical Trials (IRCT20220714055469N1). All participants provided written informed consent.

3.2. Experimental Procedures

At the beginning of the study, each participant received three new pairs of military boots manufactured by Arsan Sanat Aghanezhad, a private company in Tabriz, Iran. The new boots were distributed before baseline testing, and the same boots were reassessed after six months of use. Mechanical characteristics, including boot stiffness, were measured before and after the six-month period. Running kinematics were assessed while participants ran along an 18-m straight track at 3.2 m/s. The boots were made from rubber, polyurethane (PU), and thermoplastic polyurethane. They featured an ethylene-vinyl acetate midsole with stability plugs for cushioning and stability. The rubber outsole had molded tread patterns to improve traction and durability (13). Participants recorded the time and mileage spent wearing the boots in a daily training log. Researchers conducted regular follow-up telephone calls to verify log completion and participants' comfort with the boots. Six months later, participants returned to the laboratory for a final biomechanical assessment. Before the assessment, they completed three familiarization runs on the laboratory walkway. All analyzed trials involved running at 3.2 m/s. A trial was considered successful if the right foot landed in the center of the pressure plate and visual inspection of the online display showed no interference in the EMG recordings (14). Three successful running trials per experimental condition were included in the analysis. Subsequently, maximum voluntary isometric contraction testing was performed for each muscle to enable normalisation of the EMG signals.

3.3. Experimental Design and Electromyography Recording

Participants ran along an 18-m straight track at 3.2 m/s on two occasions: at baseline in new boots and after six months in the same worn boots. The footwear was supplied by Arsan Sanat Aghanezhad, a private manufacturer in Tabriz, Iran, and was made from rubber, polyurethane (PU), and thermoplastic polyurethane. A wireless surface EMG system (Biometrics Ltd.) with eight bipolar electrode pairs

recorded activity from eight muscles of the right leg: tibialis anterior (TA), medial gastrocnemius (Gas-Med), vastus medialis (VM), semitendinosus (ST), vastus lateralis (VL), biceps femoris (BF), gluteus medius, and rectus femoris (Figure 1).

The electrodes had an interelectrode distance of 20 mm, an impedance of 100 MΩ, and a common-mode rejection ratio > 110 dB (15). These muscles were selected because of their role in stabilizing the body during running (15). Raw EMG signals were digitized at 1000 Hz and transmitted wirelessly via Bluetooth to a computer for offline analysis. The skin over the selected muscles was shaved and cleaned with alcohol according to the SENIAM guidelines for surface electromyography (16). EMG data were synchronized. Maximum voluntary isometric contraction was measured for each muscle using a handheld dynamometer to standardize the EMG signals. Filters were applied to remove noise and interference, including a 10 - 500 Hz band-pass filter and a 50 Hz notch filter (16). Running stride waveforms were time-normalized to 51 points using a cubic spline function. The stance phase was divided into four consecutive intervals: loading (first 15%), early stance (15 - 40%), mid-stance (40 - 60%), and late stance (60 - 100%). The following kinematic variables were extracted: knee flexion angle at heel strike, peak knee flexion angle during early stance, and maximum knee extension angle during mid-stance. For kinetic analysis, the hip adduction moment was assessed during early stance, and peak flexion moments were identified during early and late stance. Additionally, peak extension occurred second in loading and overdue stance.

Muscle co-contraction is characterized by the activation ratio between agonist and antagonist muscles, the overall activation of both muscle groups, and the dominant co-contractors among agonists and antagonists. Two variables were used to examine co-contraction: 1) directed co-contraction ratios (DCCR) between agonist and antagonist muscles and 2) overall muscle activation. DCCRs were determined for the medial (SM, VM, MG)/lateral (BF, VL, LG [lateral gastrocnemius]) muscles (MLDCCR, medial/lateral directed co-contraction ratio), medial (SM)/lateral (BF) hamstrings (HAMDCCR, hamstring directed co-contraction ratio), and the knee flexors (SM, BF, MG, LG)/extensors (VL, VM) (FEDCCR, flexor-extensor directed co-contraction ratio) (12). The DCCRs were determined using the following formulas: if the average EMG activity of the agonist muscles was higher than that of the antagonist muscles, the DCCR was calculated as 1 minus the average EMG activity of the antagonist muscles divided by the average EMG activity of the agonist muscles. If the opposite was true, the DCCR was calculated as the average EMG activity of the agonist muscles divided by the average EMG

activity of the antagonist muscles minus 1. A DCCR above 0 indicated that the agonist muscles were more active than the antagonist muscles, whereas a DCCR of 0 represented maximum co-contraction. A DCCR of 1 or -1 indicated low co-contraction. Additionally, net muscle activation values were calculated by summing the activity of all agonist and antagonist muscles during each phase of gait. Instantaneous values were determined for all co-contraction measures throughout stance and averaged within each of the four stance subphases (17).

3.4. Statistical Analysis

Data normality was confirmed using the Shapiro-Wilk test. A two-way repeated-measures ANOVA was conducted with boot material (rubber, TPU, and PU) and measurement time (pre/post) as within-participant factors. Paired-sample *t*-tests with Bonferroni correction were used for post hoc comparisons. If substantial between-group differences were identified at baseline, the relevant parameter was included as a covariate. Partial eta-squared (η^2p) was converted to Cohen's *d* to determine effect sizes. According to Cohen, $d < 0.50$ indicates a small effect, $0.50 \leq d < 0.80$ indicates a medium effect, and $d \geq 0.80$ indicates a large effect. Statistical significance was set at $P < 0.05$. Analyses were performed using the Statistical Package for the Social Sciences (SPSS), version 26.0.

4. Results

General ankle co-contraction showed no significant main effects of boot type or measurement time and no significant interaction across the running phases (Table 1).

For directed ankle co-contraction, the main effect of boot type was not significant during any phase ($P > 0.05$). A significant main effect of time was observed during push-off ($P = 0.046$), with rubber boots eliciting higher co-contraction values than PU boots. A significant boot-by-time interaction was observed for directed co-contraction during loading response ($P = 0.011$) (Table 2).

5. Discussion

This study examined whether accumulated mileage in combat boots affects ankle muscle co-contraction during running. No significant effects were observed for general ankle co-contraction. For directed co-contraction, a significant time effect was observed during push-off, and a significant boot-by-time interaction was observed during the loading response.

The Gas-Med and TA muscles act in opposition to generate sagittal-plane movement. Gas-Med activation is predominantly associated with stabilization during stance,



Figure 1. Recorded Muscle activity with military boots during running

Table 1. General Co-Contraction Indices for the Ankle Joint Across All Conditions ^a

Phase	Rubber		TPU		PU		Significant (Effect Size)		
	New	Used	New	Used	New	Used	Boot Effect	Time Effect	Interaction: Boot × Time
LR	109.19 ± 30.40	107.36 ± 17.86	110.51 ± 39.49	120.31 ± 42.50	104.42 ± 22.23	123.28 ± 39.81	0.660 (0.030)	0.330 (0.034)	0.377 (0.070)
MS	103.96 ± 25.71	117.76 ± 25.58	113.35 ± 27.17	126.79 ± 49.67	107.66 ± 26.12	98.98 ± 22.50	0.109 (0.151)	0.334 (0.032)	0.142 (0.135)
PO	115.12 ± 31.43	114.01 ± 38.26	116.57 ± 18.41	108.31 ± 30.89	99.77 ± 14.25	121.82 ± 32.95	0.915 (0.007)	0.489 (0.017)	0.107 (0.153)

^a Values are expressed as mean ± SD. $P > 0.05$. Abbreviations: LR; Loading response, MS; Mid stance, PO; Push off, SD; standard deviation, TPU; thermoplastic polyurethane.

whereas TA activation primarily assists forward leg swing. Under normal conditions, their activation periods overlap minimally, resulting in little or no co-contraction. When assessing ankle plantarflexion and dorsiflexion during running, the activation patterns of Gas-Med and TA should be considered because they function as agonist and antagonist, respectively. Temporal overlap in their activation indicates co-contraction, which may occur during stance or swing (18). Previous studies have reported that TA/Gas-Med co-contraction is common during weight-bearing activities and may increase limb stability and facilitate the transition from double-limb to single-limb support (19). Co-contraction in this muscle pair has also been suggested to require minimization because the agonist muscles (dorsiflexors) dominate during this phase

(19). Some evidence suggests that co-contraction lasting less than 8% of the gait cycle may be physiologically acceptable (19). The co-contraction values observed in this study may be clinically meaningful because they occurred at a frequency similar to that reported for other stance-phase co-contraction patterns. In this study, directed ankle co-contraction during the loading response showed a significant boot-by-time interaction.

Neither directed nor general ankle co-contraction showed significant effects during mid-stance. During walking, the TA and Gas-Med muscles have been reported to act synergistically via co-contraction to stabilize the ankle-foot complex. This co-contraction occurs in approximately 32% of strides and contributes to stability during single-limb support and swing of the contralateral

Table 2. Directed Co-Contraction Indices for the Ankle Joint Across All Conditions^a

Phase	Rubber		TPU		PU		Significant (Effect Size)		
	New	Used	New	Used	New	Used	Boot Effect	Time Effect	Interaction: Boot × Time
LR	0.02 ± 0.51	0.17 ± 0.57	0.01 ± 0.54	0.16 ± 0.44	0.25 ± 0.63	0.22 ± 0.30	0.366 (0.072)	0.242 (0.048)	0.011 (0.282)
MS	0.13 ± 0.45	0.08 ± 0.46	0.32 ± 0.89	0.18 ± 0.39	0.33 ± 0.58	0.14 ± 0.41	0.397 (0.066)	0.091 (0.198)	0.250 (0.097)
PO	0.10 ± 0.71	0.04 ± 0.37	0.17 ± 0.66	0.14 ± 0.36	0.41 ± 0.65	0.18 ± 0.41	0.597 (0.037)	0.046 (0.125)	0.077 (0.173)

^a Values are expressed as mean ± SD. $P > 0.05$. Abbreviations: LR; Loading response, MS; Mid stance, PO; Push off, SD; standard deviation, TPU; thermoplastic polyurethane.

limb. During this phase, the TA acts as a foot invertor, whereas the lateral gastrocnemius acts as an ankle plantarflexor. Both muscles coordinate to maintain balance and postural control during walking (20). Di Nardo et al. (18) reported higher levels of co-contraction during mid-stance. In the present study, push-off showed a significant time effect for directed co-contraction, whereas general co-contraction showed no significant effects. There is debate regarding whether the plantar flexor muscles are primarily responsible for ankle plantarflexion and knee flexion during pre-swing. Sutherland (2001) suggested that these muscles are inactive, whereas Winter (21) posited that knee flexion during pre-swing is mediated by the plantar flexor muscles. Our results indicate that the muscles are active during pre-swing, particularly during push-off. Olney (1985) found evidence of TA/GL co-activation during pre-swing; however, this should not be interpreted as simultaneous contraction of agonist and antagonist muscles at the same joint because the TA and GL act on different joints (21).

Co-contraction occurs during various functional activities. Changes in co-contraction ratios after fatigue indicate a tendency toward agonist muscle saturation accompanied by increased antagonist contraction (22). Localized quadriceps fatigue has been reported to alter the activity ratio between the quadriceps and hamstrings. The body attempts to compensate for fatigue-related risk factors through knee muscle co-activation. Fatigue was not examined in this study. Future studies should therefore investigate its influence on ankle muscle co-contraction patterns.

Footnotes

AI Use Disclosure: Deepseek was used for translation in the introduction section at a Moderate level.

Authors' Contribution: The author conducted all aspects of the study.

Clinical Trial Registration Code: IRCT20220714055469N1.

Conflict of Interests Statement: The authors do not declare any conflicts of interest for this study.

Data Availability: The dataset presented in this study is available from the corresponding author upon reasonable request, both during the submission process and after publication.

Ethical Approval: IR.UMA.REC.1401.026.

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Informed Consent: All participants provided written informed consent.

References

- Messier SP, Martin DF, Mihalko SL, Ip E, DeVita P, Cannon DW, et al. A 2-year prospective cohort study of overuse running injuries: the runners and injury longitudinal study (TRAILS). *The American Journal of Sports Medicine*. 2018;**46**(9):2211-21. [PubMed ID: 29791183]. <https://doi.org/10.1177/0363546518773755>.
- Lopes AD. Incidence, Prevalence, and Risk Factors of Running-Related Injuries. *Incidence, Prevalence, and Risk Factors of Running-Related Injuries: An Epidemiologic Review*. 2020:1-7. <https://doi.org/10.1016/B978-0-323-67949-7.00001-X>.
- Sinclair J, Greenhalgh A, Brooks D, Edmundson CJ, Hobbs SJ. Gender differences in the kinetics and kinematics of distance running: implications for footwear design. *Footwear Science*. 2012;**6**(2):118-28. <https://doi.org/10.1080/19424280.2012.693543>.
- Sinclair J, Taylor PJ, Atkins S. Effects of new military footwear on knee loading during running. *Footwear Science*. 2015;**7**(3):165-71. <https://doi.org/10.1080/19424280.2015.1066879>.
- Sinclair J, Taylor PJ, Atkins S. Influence of running shoes and cross-trainers on Achilles tendon forces during running compared with military boots. *Journal of the Royal Army Medical Corps*. 2015;**161**(2):140-3. [PubMed ID: 25428136]. <https://doi.org/10.1136/jramc-2014-000308>.
- Sinclair J, Taylor PJ. Influence of new military athletic footwear on the kinetics and kinematics of running in relation to army boots. *Journal of Strength and Conditioning Research*. 2014;**28**(10):2900-8. [PubMed ID: 24714532]. <https://doi.org/10.1519/jsc.0000000000000477>.
- Paisis P, Hanley B, Havenetidis K, Bissas A. Cypriot and Greek Army Military boot cushioning: ground reaction forces and subjective responses. *Military Medicine*. 2013;**178**(4):e493-e7. [PubMed ID: 23707838]. <https://doi.org/10.7205/milmed-d-12-00432>.

8. Pohl MB, Mullineaux DR, Milner CE, Hamill J, Davis IS. Biomechanical predictors of retrospective tibial stress fractures in runners. *Journal of Biomechanics*. 2008;**41**(6):1160-5. [PubMed ID: 18377913]. <https://doi.org/10.1016/j.jbiomech.2008.02.001>.
9. Snyder RA, DeAngelis JP, Koester MC, Spindler KP, Dunn WR. Does shoe insole modification prevent stress fractures? A systematic review. *HSS Journal®: The Musculoskeletal Journal of Hospital for Special Surgery*. 2009;**5**(2):92-8. [PubMed ID: 19506967]. [PubMed Central ID: PMC2744752]. <https://doi.org/10.1007/s11420-009-9114-y>.
10. Busse ME, Wiles CM, van Deursen RW. Co-activation: its association with weakness and specific neurological pathology. *Journal of neuroengineering and rehabilitation*. 2006;**3**(1). 26. [PubMed ID: 17116259]. [PubMed Central ID: PMC1665451]. <https://doi.org/10.1186/1743-0003-3-26>.
11. Lo J, Lo OY, Olson EA, Habtemariam D, Iloputaife I, Gagnon MM, et al. Functional implications of muscle co-contraction during gait in advanced age. *Gait & posture*. 2017;**53**:110-4. [PubMed ID: 28129590]. [PubMed Central ID: PMC5346031]. <https://doi.org/10.1016/j.gaitpost.2017.01.010>.
12. Jafarnezhadgero AA, Hamlabadi MP, Anvari M, Zago MJG, Posture. Long-term effects of shoe mileage on knee and ankle joints muscle co-contraction during walking in females with genu varus. *Gait & Posture*. 2021;**89**:74-9. [PubMed ID: 34246175]. <https://doi.org/10.1016/j.gaitpost.2021.07.004>.
13. Hamlabadi MP, Jafarnezhadgero A, Bakhshodeh Nia I, Hassannejad H. The Effect of Three Types of Military Boots' Mileage on Knee Muscular Co-Contraction During Running. *Physical Treatments-Specific Physical Therapy Journal*. 2023;**13**(3):0-164. <https://doi.org/10.32598/ptj.13.3.348.7>.
14. Jafarnezhadgero AA, Hamlabadi MP, Sajedi H, Granacher U. Recreational runners who recovered from COVID-19 show different running kinetics and muscle activities compared with healthy controls. *Gait & Posture*. 2022;**91**:260-5. [PubMed ID: 34775229]. [PubMed Central ID: PMC8584715]. <https://doi.org/10.1016/j.gaitpost.2021.11.002>.
15. Piran Hamlabadi M, Jafarnezhadgero A. Effect of Six Months of Using Thermoplastic Polyurethane and Rubber Military Boots on Lower Limb Muscle Activities During Running. *Annals of Military and Health Sciences Research*. 2024;**22**(1). <https://doi.org/10.5812/amh-142692>.
16. Jafarnezhadgero AA, Piran Hamlabadi M. Effect of simple and sensor thoracolumbosacral braces on electromyography activity of selected muscles in patients with kyphosis during running. *J Gorgan Univ Med Sci*. 2022;**24**(2):24-30.
17. Emami S, Jafarnezhadgero A, Piran Hamlabadi M. The effect of knee orthosis on co-contraction values of knee and ankle muscles during running in people with knee deformity in the frontal plane. *Iranian Journal of Rehabilitation Research in Nursing*. 2022;**8**(4):76-87. <https://doi.org/10.22034/IJRN.8.4.76>.
18. Di Nardo F, Mengarelli A, Maranesi E, Burattini L, Fioretti S. Assessment of the ankle muscle co-contraction during normal gait: A surface electromyography study. *Journal of Electromyography and Kinesiology*. 2015;**25**(2):347-54. [PubMed ID: 25465985]. <https://doi.org/10.1016/j.jelekin.2014.10.016>.
19. Schmitz A, Silder A, Heiderscheid B, Mahoney J, Thelen DG. Differences in lower-extremity muscular activation during walking between healthy older and young adults. *Journal of electromyography and kinesiology*. 2009;**19**(6):1085-91. [PubMed ID: 19081734]. [PubMed Central ID: PMC3689417]. <https://doi.org/10.1016/j.jelekin.2008.10.008>.
20. Nardo FD, Mengarelli A, Ghetti G, Fioretti S, editors. Statistical analysis of EMG signal acquired from tibialis anterior during gait. XIII Mediterranean Conference on Medical and Biological Engineering and Computing. 2013. p. 619-622.
21. Winter DA. Anthropometry. *Biomechanics and motor control of human movement*. 2009. <https://doi.org/10.1002/9780470549148>.
22. Gagnon D, Bertrand Arsenault A, Smyth G, Kemp F. Cocontraction changes in muscular fatigue at different levels of isometric contraction. *International Journal of Industrial Ergonomics*. 1992;**9**(4):343-8. [https://doi.org/10.1016/0169-8141\(92\)90066-9](https://doi.org/10.1016/0169-8141(92)90066-9).