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Plantar Pressure Distribution and Posture Stability Analysis in a Construction Roofing Task

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Abstract

Roofing tasks on inclined surfaces expose workers to significant biomechanical risks, particularly for novice roofers who lack experience in managing balance and weight distribution on sloped surfaces. This study investigates the impact of varying roof slopes (0°, 15°, and 30°) on plantar pressure distribution across distinct foot zones (toe, metatarsal, midfoot, and heel) among novice roofers, aiming to enhance safety by identifying critical pressure areas under sloped surfaces. Findings reveal that increased slope generally reduces overall plantar pressure, yet high peak pressure remains concentrated in the toe area across all slopes, suggesting a reliance on toe pressure for stability. While metatarsal pressures are higher on flat surfaces and lower on steeper slopes, toe pressure remains consistently elevated, indicating potential for strain-related injuries. These results align with prior studies highlighting the toe's role in stabilizing on inclined surfaces, suggesting the need for ergonomic interventions. Tailored footwear and training on weight distribution strategies may reduce injury risks and improve stability. Despite a limited sample size, the study contributes foundational data for ergonomic guidelines in roofing to reduce injury risk, improve balance, and enhance comfort for novice roofing workers.

Keywords: Plantar pressure, Ergonomics, Construction roofers, Balance posture, Center of pressure

Introduction

In roofing and construction tasks on inclined surfaces, maintaining stability while minimizing pressure on specific foot zones is essential for worker safety and ergonomics. Foot pressure distribution and balance adaptation in such tasks remain underexplored, especially among novice roofers who lack experience-based adaptive mechanisms. With steeper slopes, workers must adjust their balance and foot pressure patterns to decrease injury risk and increase task efficiency. This study examines how various roof slopes impact plantar pressure across foot zones, with a focus on the toe, metatarsal, midfoot, and heel, using a male sample to reflect roofers' demographics. By analyzing average and peak pressures across these zones, we aim to identify critical pressure areas and inform ergonomic interventions to reduce strain and improve stability. Workers in roofing occupations face a significantly elevated risk of musculoskeletal disorders, with incidence rates surpassing those of other construction trades by 30% (Wang et al., 2015). The top three musculoskeletal pains (MSPs)for roofers were foot, back, and knee pain (Kayastha & Kisi, 2024). Novice roofers, with limited experience in balance and weight distribution on slopes, face elevated risks of biomechanical strain and falls. While previous research addresses foot pressure in construction, data on roof slope-specific plantar pressure patterns for novice workers is sparse. This study addresses this gap by examining three roof slopes (0°, 15°, and 30°) to understand plantar pressure distribution and its effect on postural stability. The findings will inform ergonomic interventions, including footwear adaptations and training programs, contributing to safer practices for novice roofers adapting to inclined work environments.

Literature Review

Compared to other construction occupations, roofing is viewed as an exceptionally high-risk field, as roofing workers face a fatality rate more than triple the norm for the construction sector as a whole (Dong et al., 2013; Fredericks et al., 2005; Moore & Wagner, 2014). Roofing, a high-risk construction occupation, demands complex load management on sloped surfaces, heightening the risk of biomechanical strain. Roofing is among the most hazardous occupations, with high injury rates exacerbated by sloped, uneven surfaces and strenuous postures. Roof workers are at significant risk of falling from the edge (Kayastha & Kisi, 2024). According to the Bureau of Labor Statistics (BLS) in the United States, roofing fatalities rose by 7.8% in 2021 (BLS, 2022), underscoring the need for enhanced safety measures. Roofers commonly adopt various postures, such as stooping, kneeling, standing, squatting, and crawling, during tasks like shingle installation and other roofing activities. Among these, stooping and kneeling are particularly prevalent due to their frequent use in tasks requiring extended reach and stability (Wang., 2017). Stooping, characterized by awkward bending, ranks as one of the top five ergonomic challenges (Zimmerman et al., 1997). This review examines recent findings on plantar pressure distribution and stability in construction and identifies gaps that limit effective ergonomic intervention, particularly for novice roofers.

Research on plantar pressure as a measure of biomechanical risk is growing, particularly in high-strain occupations. Choi et al. (2015) emphasized that plantar pressure data provides critical insights into weight-bearing adjustments, essential for tasks on inclined surfaces. Newer studies, such as that by Simon et al. (2024), support that elevated plantar pressure in specific foot zones (e.g., toe, metatarsal) correlates with postural adaptations necessary to counteract sloped surfaces. However, this work primarily focuses on general or experienced populations, with limited application to novices lacking adaptive mechanisms.

Studies increasingly show that slope angles dramatically impact plantar pressure distribution. Sen et al. (2015) highlight that with the increase in gradient plantar pressure at various foot regions increased gradually in both feet in comparison to level walking, and maximum plantar pressure observed in heel region in both feet in comparison to other studied regions These findings align with the foundational work of Koo (2019), who quantified the effects of incline and body posture on peak foot pressure zones. A recent systematic review by Orr et al. (2022) further supports these findings, noting an increased biomechanical load in tasks that require frequent repositioning of the feet, yet lacking specific applications for novice roofers.

Novice roofers face heightened risks in managing plantar pressure distribution due to their limited experience. Unlike experienced workers who intuitively adjust to slopes, novices often experience elevated pressure in the forefoot zones, an imbalance highlighted in recent construction safety studies by Choi et al. (2016). Although Breloff et al. (2019) and Dutta et al. (2020) highlight knee health risks from sloped surfaces and kneeling, they overlook how different roof slopes affect plantar pressure across foot zones.

Research Gap

While extensive research has examined plantar pressure in general construction tasks, studies specifically addressing the effect of slope angles on novice roofers remain limited. Current studies largely focus on experienced workers, limiting the applicability of interventions to novices who face higher instability and strain risks on inclined surfaces. Additionally, inadequate knowledge of how different roof slopes affect plantar pressure distribution across foot zones heightens the risk of injury, fatigue, and reduced stability, especially during postures like stooping.

Research Objective

The primary objective of this study is to examine how varying roof slope angles (0°, 15°, and 30°) influence plantar pressure distribution across distinct foot zones (toe, metatarsal, midfoot, and heel) in novice roofers. By analyzing both average and peak plantar pressures across these foot zones, this study aims to understand the impact of slope on postural stability and pressure concentration in the foot, particularly in high-risk zones. Insights from this research will inform the development of slope-specific ergonomic guidelines to reduce injury risk, improve balance, and enhance comfort, especially for novice roofers.

Methodology

A total of nine healthy male volunteers participated in the study, with an average age of 27 years (±5 years), an average height of 165 cm (±3.62 cm), and an average weight of 70 kg (±10 kg). All participants had no history of chronic low back injury, ankle injuries, joint concerns or feet injuries. This research protocol was approved by the Institutional Review Board (IRB) of the University. As over 97% of roofers are male (BLS, 2017), females were excluded in the study. Sample size is smaller in this study due to the limitation of volunteering challenges and time-intensive nature of data collection (1 hour long physical experiment), logistical challenges, safety considerations. Similar studies used less than ten sample sizes such as Breloff et al. (2019), Antwi-Afari et al. (2020), and Dutta et al. (2023).

Experiment Set Up and Data Collection

The study was conducted in a simulated laboratory environment using a roof mockup designed to investigate plantar pressure patterns during roofing tasks. The mockup accommodated three distinct slope angles (0°, 15°, and 30°) for testing purposes (see Figure 1a, Figure 1b, and Figure 1c) Participants performed one-minute trials at each slope angle while maintain stooping postures, characterized by forward bending at the waist with relatively straight legs, simulating typical shingle installation movements.

Figure 1a. Stooping at 0°

Figure 1b. Stooping at 15°

Figure 1c. Stooping at 30°

The stooping posture was chosen for this pilot study as it closely replicates the typical working position of roofers during shingle installation and other roofing tasks. In addition, variation on plantar pressure distribution across the four-foot anatomical regions (Choi et al., 2015) can be significantly noticed and compared. Each participant completed three trials total, one at each slope angle, while wearing a XSensor Wearable Insole Pressure System from Sensor Technology Corporation. Data collection was conducted using the Sensor Wearable Insole and software. The study focused on two key independent variables: roof slope (0°, 15°, and 30°) and working posture (stooping position during shingle installation). Bilateral plantar pressure data were recorded for both feet, resulting in a total of 24 plantar pressure distributions across all slope conditions for the data analysis.

Data Analysis

This study examined cumulative Center of Pressure (COP) distribution patterns across 0°, 15°, and 30° sloped surfaces and analyzed related data on average and peak pressures to provide insights into foot pressure distribution and stability dynamics during stooping tasks. Average pressure is the mean pressure during the contact phase across specific foot regions, whereas Peak pressure identifies the maximum pressure recorded with each foot region. The COP is a point representing the average location of the forces exerted by the foot on the ground.

COP distribution maps revealed that, at each slope angle, the highest COP concentrations were observed in specific foot zones, predominantly midfoot regions (see Figure 2). These maps indicate how weight and stability are managed across the foot under various incline conditions. As the slope increased, there was a slight shift in COP, suggesting that participants adjusted their balance and weight distribution to maintain stability, indicating a compensatory response to the incline.

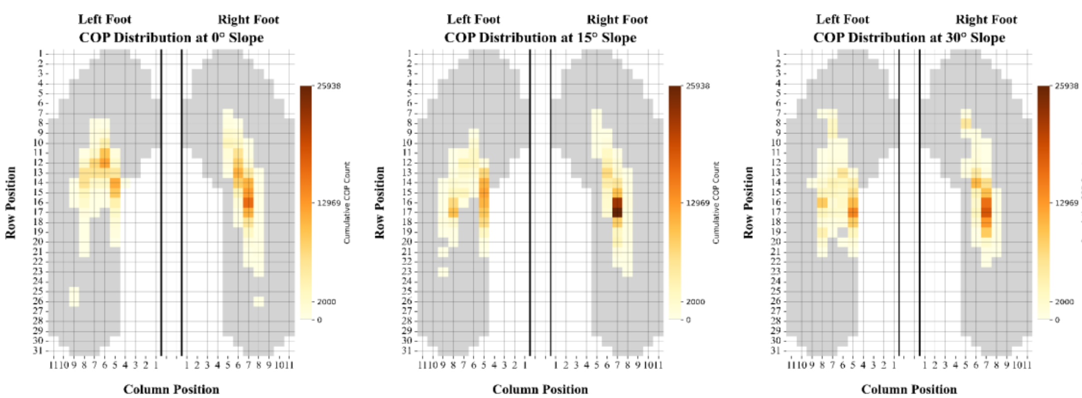

Figure 2. Cumulative COP distribution patterns during stooping tasks

These observations were further validated through a two-way ANOVA for average and peak pressure analysis.

Statistical Analysis for Average Pressure

A two-way ANOVA was conducted to assess the effects of two independent slopes (0°, 15°, and 30°) and foot zone (toe, metatarsal, midfoot, and heel)—on the dependent variables of average and peak plantar pressures during the stooping task. A univariate ANOVA was applied to measure the individual and interactive impacts of these factors on average and peak pressures. Prior to performing the ANOVA, assumptions such as normality, homogeneity of variance, and independence of observations were evaluated.

Two-Way ANOVA Results for Average Pressure and Peak Pressure

Slope Angle Effects

The ANOVA revealed a significant main effect of slope angle on average pressure, $F(2, 588) = 9.856$, $p < .05$, $\eta^2 = .032$, suggesting average pressure varies significantly across slope angles (See Table 1). A descending trend in average pressure was observed as slope angle increased, with the highest average pressure at 0° and the lowest at 30° (see Figure 3). Tukey's HSD post-hoc tests indicated significant differences between the 0° and 15° slopes (mean difference = 0.258, $p < 0.05$) and between the 0° and 30° slopes (mean difference = 0.451, $p < 0.05$).

Table 1. Between-subjects effects (two-way ANOVA Results):

Source	**Type III Sum of squares**	**df**	**Mean square**	**F**	**Sig.**	**Partial eta squared**
Corrected model	327.634[a]	11	29.785	28.612	0	0.349
Intercept	5854.512	1	5854.512	5623.97	0	0.905
Slope angle	20.52	2	10.26	9.856	0	0.032
Foot zone	215.899	3	71.966	69.132	0	0.261
Slope angle x Foot zone	91.216	6	15.203	14.604	0	0.13
Error	612.103	588	1.041			
Total	6794.249	600				
Corrected Total	939.737	599				

Foot Zone Effects

A highly significant main effect was observed for foot zone, $F(3, 588) = 69.132$, $p < .05$, $\eta^2 = .261$, indicating substantial pressure variations across foot regions. Tukey HSD tests confirmed significant differences among foot zones ($p < .05$ for most comparisons). Profile plots showed the metatarsal area consistently experiencing the highest pressure, followed by variations in the heel, midfoot, and toe being the lowest (see Figure 3).

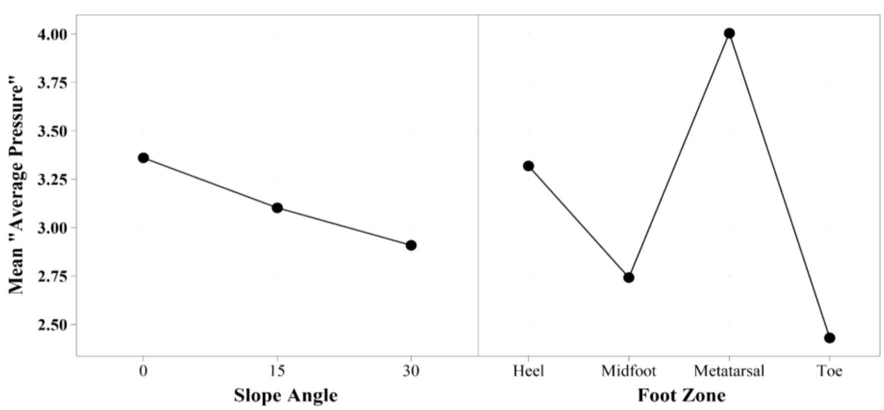

Figure 3. Average pressure vs Slope angles and foot zone

Interaction Effects: Slope Angle vs. Foot Zone

A significant interaction effect was observed between slope angle and foot zone, $F(6, 588) = 14.604$, $p < .05$, $\eta^2 = .130$. This interaction suggests that the relationship between slope angle and average pressure varies by foot zone. Profile plots indicated that metatarsal pressure consistently decreased with steeper slopes (see Figure 4).

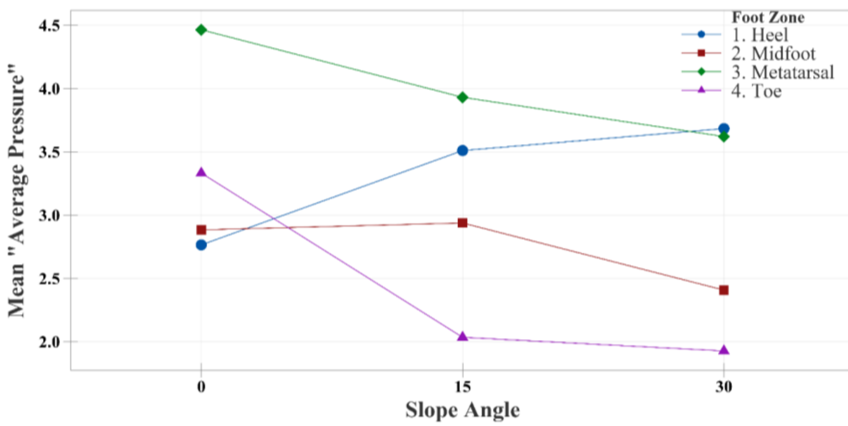

Figure 4. Interaction plot of slope angle and foot zone on average pressure

Two-Way ANOVA for Peak Pressure

Slope Angle Effects

The ANOVA showed a significant main effect of slope angle on peak pressure, $F(2, 588) = 13.947$, $p < .05$, $\eta^2 = .045$, indicating peak pressure differences across slope angles. Tukey's HSD tests revealed significant differences between 0° and both 15° and 30° slopes (mean differences = 1.958 and 1.926, respectively, $p < .05$) (See Table 2). The slope angle plot indicated that peak pressure was highest at 0° and decreased at 15° and 30°(see Figure 5).

Table 2. Between-subjects effects (two-way ANOVA Results):

Source	Type III Sum of squares	df	Mean square	F	Sig.	Partial eta squared
Corrected model	3900.277a	11	354.571	19.667	0	0.269
Intercept	67912.661	1	67912.661	3766.85	0	0.865
Slope angle	502.919	2	251.46	13.947	0	0.045
Foot zone	2996.847	3	998.949	55.408	0	0.22
Slope zngle x Foot zone	400.511	6	66.752	3.702	0	0.036
Error	10601.066	588	18.029			
Total	82414.004	600				
Corrected total	14501.343	599				

Foot Zone Effects

A substantial main effect was also observed for foot zones, $F(3, 588) = 55.408$, $p < .05$, $\eta^2 = .220$, showing significant peak pressure variations across foot regions (see Table 2). Tukey HSD post-hoc comparisons revealed notable differences among foot zones (e.g., toe vs. midfoot and toe vs. heel). Profile plots illustrated that the toe region experienced the highest peak pressure, while the midfoot consistently showed the lowest (see Figure 5).

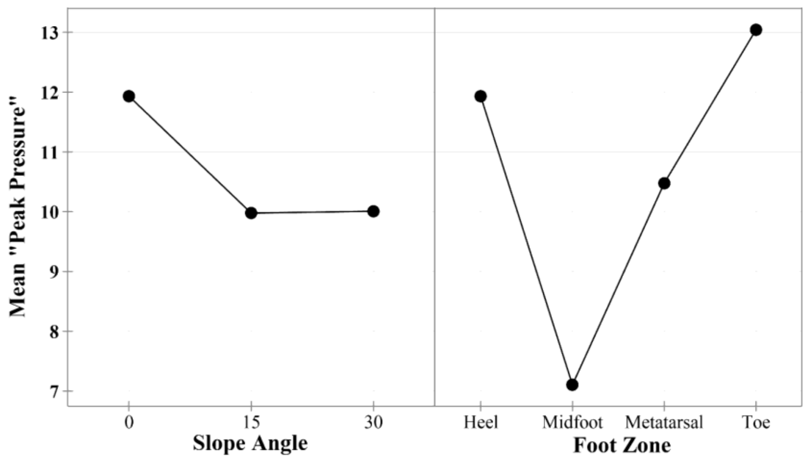

Figure 5. Peak pressure vs slope angles and foot zone

Interaction Effects: Slope Angle vs. Foot Zone for Peak Pressure

A significant interaction was found between slope angle and foot zone, $F(6, 588) = 3.702$, $p < .05$, $\eta^2 = .036$, suggesting that the relationship between slope angle and peak pressure varies by foot zone (see Table 2). Interaction plots showed that each foot zone responded differently to slope angle changes (see Figure 6). For example, while the toe consistently exhibited high pressure across slopes, the midfoot showed a more pronounced decrease in peak pressure with increasing slope angle. The heel exhibited moderate peak pressure levels across all slopes, with minor variations, suggesting that metatarsal stability is less affected by slope changes compared to other zones.

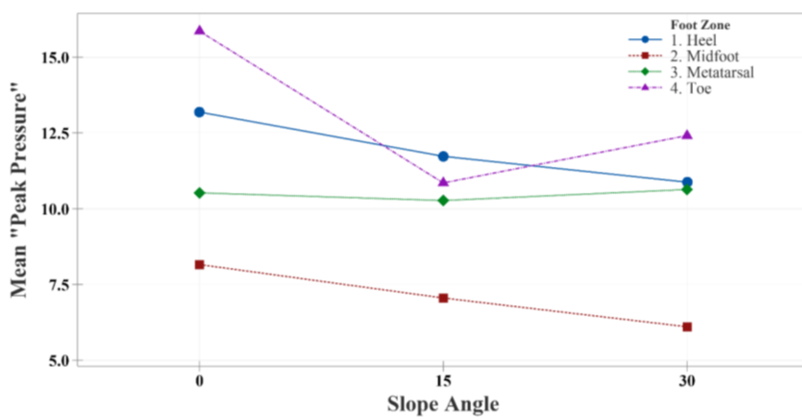

Figure 6. Interaction plot of slope angle and foot zone on peak pressure

Discussion

This study investigated the impact of varying roof slopes (0°, 15°, and 30°) on plantar pressure distribution across foot zones (toe, metatarsal, midfoot, and heel) in novice roofers. The data (see Figure 3) showed a relationship between slope steepness and average pressures. the highest pressures recorded on flat surfaces (0°) and marked reductions at 15° and 30° inclines. These findings challenge conventional assumptions about pressure distribution on slopes. Moreover, the most striking discovery emerged in the dynamic relationship between heel and metatarsal regions (see Figure 4). The metatarsal pressure showed a notable decrease as slope angles increased, whereas the heel region maintained relatively stable pressure levels across different slopes. The most significant pressure reduction, approximately 42%, occurs in the toe region as slope angle increases. These results suggests that pressure distribution shifts significantly away from the toes on steep slopes. This trend suggests that as slope angle increases, novice workers intuitively adjust their weight distribution to enhance stability, which aligns with findings by Choi et al. (2015). This relationship may be crucial for designing footwear or insoles tailored to the task activities (Arceri et al., 2024). This adaptation can reduce stress on specific zones by incorporating adaptive cushioning in the metatarsal and heel areas to better support the load redistribution occurring on inclines, thereby potentially mitigating musculoskeletal risks.

The peak pressure analysis further indicates that while pressures generally decrease on inclined surfaces (see Figure 5), the toe region remains under significantly high peak pressure across all slopes. Particularly, the toe region emerged as the area experiencing the highest peak pressure, maintaining this characteristic consistently across all slope angles, which contrasts with the general trend of pressure reduction on inclined surfaces. Koo (2019) indicated that the peak pressure on MFF (Medial forefoot that contains Toe) was significantly affected by walking speed and by the combination of walking speed and slope. The consistently high toe pressure suggests that novice workers rely on the toe area for balance, especially on sloped surfaces.

The interaction between slope angle and foot zone provides additional insights. While metatarsal pressure steadily decreases with steeper slopes, other areas, particularly the toe, maintain higher peak pressures (see Figure 6). Simeonov et al. (2003) also found that increased slope angles reduce the effective base of support, limiting the body's center of gravity movement and increasing instability risks. A reduction in contact surface area, as Fernandez (2014) noted, may further lead to poor pressure distribution, emphasizing the need for supportive gear and techniques to manage these changes. Overall, this study contributes valuable insights into how roof slope variations influence plantar pressure distribution, critical for advancing safety and ergonomics in roofing tasks.

Limitations

This study's limitations include a relatively small sample size of nine participants, potentially limiting generalizability. A larger, more diverse sample in real-world conditions would enhance external validity. Additionally, this study’s laboratory setting and focus on a single stooping posture may not fully capture the variability of real roofing environments, which typically involve multiple postures and environmental challenges. The authors plan to include more samples in the advanced study expanding this analysis to additional common roofing postures, such as kneeling and standing, could improve the applicability of the findings.

Conclusion

This study provides essential insights on how slope angles influence plantar pressure distribution among novice roofers. Our findings show that roof slopes significantly impact plantar pressure distribution across the foot zones, with increased slope angles leading to reduced pressures in most foot regions, except for consistently high pressures in the toe area. The high toe pressures across all slopes indicate that novices rely on their toes for balance, potentially increasing strain-related injury risks over time. Moreover, the metatarsal area showed higher pressure readings on flat surfaces, with a marked decrease as slopes increased, underscoring an adaptive weight distribution mechanism in response to incline changes. These trends show that beginners naturally adjust their movements, likely to stay balanced. However, they also point out areas that might be strained due to pressure build-up, as found in other studies (Choi et al., 2015; Koo, 2019). This adjustment matches previous research on how pressure helps maintain balance on sloped surfaces and the extra risks beginners face when they lack experience-based adjustments. Since slopes increase the chance of imbalance by changing foot pressure, there is a clear need for ergonomic solutions or footwear designed to provide support on high-pressure areas like toe and metatarsals. Our insights from this research will inform the development of slope-specific ergonomic guidelines to reduce injury risk, improve balance, and enhance comfort, especially for novice roofing workers in roofing industries.

Future Research

Future research should broaden this study's scope by incorporating additional postures like kneeling, standing, and walking to capture a comprehensive range of plantar pressure patterns in roofing tasks. Incorporating factors such as age, work experience, body mass index, and biomechanical measures (e.g., center of pressure, sEMG, IMU signals) in real-world settings with experienced roofers would enhance the findings' practical relevance, providing detailed insights critical to advancing workplace safety and ergonomics in the roofing industry.

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