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Site-Specific Effects of Swimming on Bone Density in Female Collegiate Swimmers

Margaret Miller*, Sarah Kojetin*, and Lesley Scibora‡

Department of Health and Exercise Science, University of St. Thomas, St. Paul, MN, USA

*Denotes undergraduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 13(1): 249-259, 2020. While swimming provides numerous cardiovascular and overall health benefits, past research suggests it provides no constructive benefits to bone strength and density at dual energy x-ray absorptiometry (DXA) measured hip and lumbar spine sites when compared to sedentary individuals. However, little research has focused on skeletal sites stressed by muscle forces during swimming such as the humerus, hip, and radius. The purpose of this study was to investigate site-specific bone strength adaptations among female collegiate swimmers compared to sedentary controls. Bone geometry and strength were assessed by DXA and peripheral quantitative computed tomography (pQCT) in ten female collegiate swimmers and ten sedentary controls (<150 minutes/week of moderate-to-vigorous physical activity) ages 18-23 years. There were no significant differences between groups in the DXA-derived outcomes. Among pQCT-measured sites, the control group had a 14.8% greater bone cortical area and 6.1% greater cortical volumetric density compared to swimmers (both $p<0.05$) at the proximal tibia (66%) site. Hip structural analysis was also performed to observe the strength and loading power at the narrowest part of the proximal femur, but no significant differences were found between groups. With no significant bone density or strength differences between groups at the humerus, radius, or distal tibia sites, this research suggests that swimming may not have osteogenic benefits, even at site-specific locations commonly stressed during the sport. For overall health, these results suggest that swimming should be supplemented with weight-bearing and resistance exercises to preserve bone strength and prevent deterioration of bone as one ages.

KEY WORDS: DXA, pQCT, hip structural analysis, bone microarchitecture, bone strength, sport

INTRODUCTION

Building and maintaining optimal bone mineral density is integral in guarding against age-related bone loss. Excess loss of bone mineral density and strength can lead to osteoporosis, defined as the loss of bone density, deterioration of bone microarchitecture, and an increased risk of fracture. According to the National Osteoporosis Foundation, approximately 54 million adults in the United States are diagnosed with osteoporosis, and fractures secondary to osteoporosis occur in nearly half of women over 50 years of age (11). Currently 19 billion dollars are spent every year on bone breaks due to osteoporosis (11). Research unequivocally shows that regularly engaging in weight-bearing physical activity such as soccer, running, or gymnastics as opposed to non-weight-bearing activity such as cycling or swimming during adolescence builds bone strength (8, 14). However, it is important to identify the extent to which non weight-bearing forms of physical activity may be beneficial to bone health.

Bone strength is determined by quantity of bone material present as well as the quality of that material (mineralization, fatigue damage, etc.). Frost's mechanostat theory of bone functional adaptation states that bone adapts its strength to the mechanical loads (i.e., ground reaction forces and muscle contractions) placed upon it through changes in bone mineral density and geometry (6). Weight-bearing physical activities are well established for building bone strength and reducing the risk of age-related bone loss (8, 14). Swimming is a popular exercise for people of all ages and abilities as it provides extensive cardiovascular benefits while minimizing stress on joints. However, as a non-weight-bearing activity, swimming has been shown to exert minimal osteogenic benefits on bone mineral density (BMD) at the lumbar spine, proximal femur, radius, and tibia, when comparing adolescent and young adult swimmers to athletes participating in weight-bearing activities and sports or sedentary controls (4, 9, 10, 15). Because adolescence is the time of peak bone mineral accrual if bones are adequately stressed (7), it is important to observe the effects of different sports in this age population.

Dual energy x-ray absorptiometry (DXA) is considered the gold standard for bone health assessment by providing two-dimensional areal bone mineral density (aBMD, g/cm^2) outcomes at clinically relevant fracture sites including the hip, spine, and forearm. Studies of athletes participating in weight-bearing sports such as gymnasts, volleyball, running, football, and soccer show significantly higher aBMD at the proximal femur, lumbar spine, and whole body when compared to swimming athletes (3, 4, 9, 10, 18). Further, one study showed femoral neck aBMD in swimmers to be no different or lower than sedentary and non-athlete control groups (17). Studies using peripheral quantitative computed tomography (pQCT) provide three-dimensional outcomes, including volumetric bone density (vBMD, mg/cm^3) and bone geometry (e.g., bone cross-sectional area) (5, 14, 16). Oosthuyse and colleagues found that while total bone area and cortical area at the radius of swimmers are 14.6% greater than controls, there were no differences at the tibia (15). When compared to athletes in weight-bearing sports (skiing, volleyball, hurdling, racquet sports, and soccer) swimmers had significantly lower tibia cortical area and cortical thickness that was not different than controls (14, 16).

While most studies have measured clinically relevant skeletal sites, little is known about the potential osteogenic effects of swimming on bone sites, such as the humerus, which may reflect site-specific bone adaptations secondary to mechanical load from upper arm and shoulder muscle contractions. Therefore, the aim of this study is to compare areal bone mineral density outcomes among female collegiate swimmers and age-matched sedentary controls at the hip and lumbar spine using DXA. We also extend pQCT-based studies that have measured volumetric bone mineral density, geometry, and bone strength at the forearm and lower leg to the mid-humerus (14). Based on previous research, we hypothesize that swimmers will show greater bone density at the hip, humerus, and radius sites compared to a control population, but lower bone density in the tibia.

METHODS

Participants

Ten female swimmers on the University of St. Thomas swim team and ten age-matched female controls from the University of St. Thomas were recruited for participation in this cross-sectional study. Swimmers were required to be current athletes on the Division III university swim team and without injury. The control group was comprised of sedentary individuals who self-reported in a questionnaire to currently engaging in 150 minutes or less of moderate physical activity each week, guidelines defined by the American College of Sports Medicine (ACSM). Additionally, swimmers were asked to provide information about years of participation in competition, injuries, primary stroke, and current time spent in the pool and weight room. Both groups reported weekly calcium intake estimated based on milligram of calcium per serving size of various foods, drinks, and supplements. The study was approved by the Institutional Review Board at the University of St. Thomas, and all participants provided informed consent prior to participation in the study. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (12). Weight and height, demographic data, past and current physical activity and sport participation, and calcium intake were collected.

Protocol

All scans were taken of the non-dominant site as this is a standard protocol when completing DXA and pQCT scans. Better comparisons can be done in doing so, because previous literature also scans the non-dominant site. First, radius length was estimated by ulnar measurement of olecranon to styloid process with the arm flexed to ninety degrees, humerus length was measured from acromion process to olecranon with the arm flexed to ninety degrees, and tibia length was measured from tibial plateau to medial malleolus. Hip and radius scans using DXA (Hologic Inc.) were performed using standardized protocols, and automatic analysis was utilized to obtain data from the femoral neck and greater trochanter regions of interest (ROI's) of the hip and distal 1/3 ROI of the radius. Radius, humerus, and femoral neck sites were scanned using DXA. Variables collected were bone mineral density (BMD) and bone mineral content (BMC).

Using the hip structural analysis (HSA) protocol on DXA, analysis was performed at the femoral narrow neck, the narrowest part of the proximal femur. Automatic analysis was used, and adjustments to ROI's were made as necessary. The following properties were obtained: 1) femoral narrow neck cortical thickness (CT) at the narrowest region; 2) cross sectional area (CSA), defined as the total bone surface area excluding trabecular and soft tissue area; 3) cross sectional moment of inertia (CSMI) which represents the structural rigidity considering the distribution of mass; and 4) buckling ratio (BR) which is a ratio of the outer radius to the cortical thickness (18).

PQCT (Norland/Stratec XCT-3000; Orthometrix, Inc. White Plains, NY) scans were acquired using a 2.3-mm slice at the distal (4%) and proximal (66%) sites of the left tibia, midshaft (33% and 50%, respectively) of the radius and humerus. A 30-mm planar scout view was obtained over the joint line for placement of the anatomic reference line. Based on bone length, the tibia distal (4%) and proximal (66%), and proximal radius (33%) locations were identified by the scanner. The midshaft humerus (50%) was identified based on bone length and scanned without a scout view. A scan speed of 25 mm/s and sampling resolution (voxel size) of 0.4 mm were used. Analysis modes and thresholds for outcomes were chosen based on manufacturer's recommendations. The mid-humerus (50%), proximal radius (33%), and proximal tibia (66%) sites were scanned using pQCT. Variables collected were cortical area (CoA), cortical density (CoD), cortical thickness (CoT), and the bone strength and strength strain index (SSI), a measure of bone strength.

Statistical Analysis

Statistical analysis was performed using SPSS IBM Statistics (version 25). Based on the sample size, the power of the present study was 0.097, with an effect size D = 0.3, using a mean difference of 13 mg/cm^3 in cortical density at the humerus found by Nikander et al. (13). Total daily calcium was calculated by adding serving sizes per week plus supplements and diving by seven. Total physical activity was reported as number of minutes for the sedentary group and hours for the swimmers. An independent sample t-test was completed to compare means for all descriptive demographic data as well as the calcium and physical activity data. Analysis of bone outcomes was done first with an independent sample t-test to compare unadjusted means. An analysis of co-variance (ANCOVA) test was done to compare DXA bone outcomes adjusted for participant height and pQCT outcomes adjusted for bone length. The statistical significance level was set at $p<0.05$.

RESULTS

Descriptive characteristics comparing the demographic data of the control participants and swimmers are presented in Table 1. Differences in height, weight, BMI, age, and calcium intake were not significant between the groups. Considering time in the pool and weight room together, swimmers completed an average of 15.7 more hours of physical activity each week than the non-athlete control participants. 80% of swimmers reported freestyle as their primary stroke, and the mean time spent participating in the sport was 11.89 years.

Unadjusted DXA-derived bone outcomes by group are presented in Table 2. No significant differences were found in the data derived from DXA. Though the difference was not significant, the BMD at both the radius and the femoral neck were lower in swimmers than control participants by 1.5% and 5.4%, respectively.

No significant differences were found in the HSA data, shown by Table 3. Swimmers did have minimally larger CSA, CSMI, and CT but not a larger BR, which was 12.7% larger in controls than swimmers.

Unadjusted pQCT-derived bone outcomes are presented in Table 4. Significant differences were found only at the 66% tibia site. The CoD of the swimmers was 6.0% less than controls ($p<0.001$) (Figure 1B). Likewise, the CoA of the swimmers was 13.8% less ($p<0.05$) than that of the control group (Figure 1A). Notably, no significant differences were found for any variables at the 50% humerus. The 33% radius site, when measured with pQCT, showed a 2.4% greater CoD in the swim group (p=0.051). It should be noted that DXA found a 1.5% greater BMD in the control group (p=0.99) at the 33% radius site, a discrepancy between the two scanning methods.

Table 1. Demographic Characteristics

	Swimmers	Controls
Age (years)	19.7±1.34	20.8±0.79
Height (cm)	168.27±6.43	168.65±10.21
Weight (kg)	65.09±7.35	68.97±15.35
BMI (kg/m^2)	22.98±2.12	24.05±3.60
Ca^{2+} Intake (mg/day)	1228.53±438.97	977.22±330.75
Physical Activity (min/week)	-----	108.00±42.90
Pool Hours (hr/week)	13.89±1.45	-----
Weight Room Hours (hr/week)	3.56±2.13	-----

Values are presented as means (±SD) with *p*<0.05. For both groups, n=10. The time spent in the pool and the weight room along with weekly physical activity was reported by swimmers, both as estimated averages. Together, they indicate total weekly physical activity time.

Table 2. DXA-derived Bone Outcomes by Group

	Swimmers	Controls	*p*-value (p<0.05)
Radius 33%			
BMC (g)	3.39±0.35	3.39±050	0.99
BMD (g/cm^3)	0.67±0.02	0.68±0.05	0.09
Neck of the Proximal Femur			
BMC (g)	4.33±0.59	4.65±0.74	0.29
BMD (g/cm^3)	0.87±0.10	0.92±0.10	0.81

Values presented are means (±SD). For both groups, n=10.

Table 3. HSA Outcomes at the Femoral Neck by Group

	Swimmers	Controls
Cross Sectional Area (cm^2)	3.04±0.51	2.91±0.32
Cross Sectional Moment of Inertia (cm^4)	1.91±0.75	1.8±0.40
Cortical Thickness (cm)	0.23±0.02	0.21±0.03
Buckling Ratio	6.55±0.83	7.38±1.13

Values presented are means (±SD). For both groups, n=10. No significant differences were observed between groups when *p*<0.05.

Table 4. PQCT-derived Bone Outcomes by Group

	Swimmers	Controls	*p*-value ($p<0.05$)
Tibia 66%			
Cortical Area (mm^2)	270.07±13.49	313.19±14.24	0.045*
Cortical Density (mg/cm^3)	1074.35±7.96	1143.05±8.40	0.000*
Cortical Thickness (mm)	4.57±0.19	4.96±0.20	0.179
SSIp (mg/mm^4)	2121.46±134.20	2178.62±134.30	0.764
Tibia 4%			
Total Area (mm^2)	139.39±25.44	141.63±26.85	0.953
Total Density (mg/cm^3)	506.96±35.51	538.08±38.54	0.571
Humerus 50%			
Cortical Area (mm^2)	178.03±6.84	172.48±7.24	0.596
Cortical Density (mg/cm^3)	1170.45±12.32	1173.04±13.03	0.890
Cortical Thickness (mm)	4.07±0.14	4.03±0.15	0.856
SSIp (mg/mm^4)	885.96±55.23	868.50±58.39	0.835
Radius 33%			
Cortical Area (mm^2)	78.39±3.35	85.01±3.55	0.215
Cortical Density (mg/cm^3)	1191.31±8.55	1163.64±9.07	0.051
Cortical Thickness (mm)	3.12±0.13	3.46±0.13	0.097
SSIp (mg/mm^4)	215.42±13.16	227.00±13.95	0.574

Values presented are means (±SD). For swimmer, n=10; for controls n=9. [=]One scan in the control group was not able to be analyzed due to movement. Significant group differences are indicated by *.

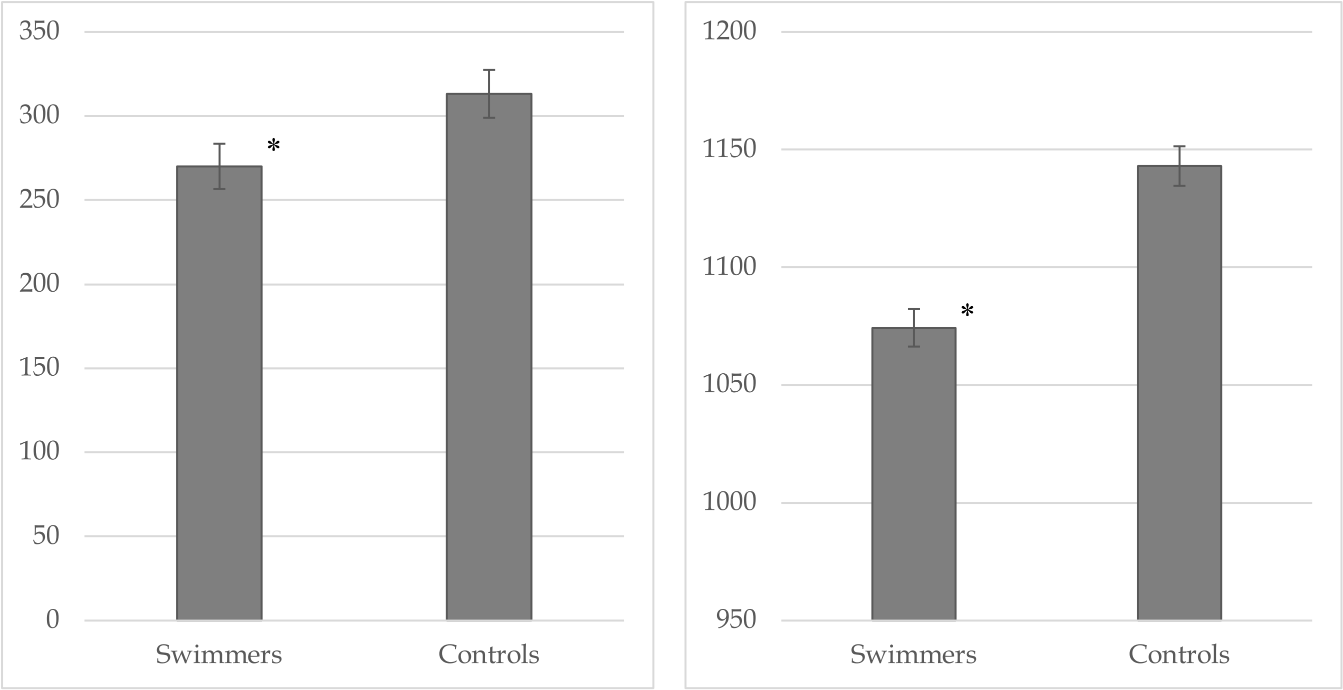

Figure 1. Significant outcomes, CoA and CoD, at the 66% tibia site.
pQCT-derived results showed significant differences ($p> 0.05$) between the swimmer and control populations in the 66% tibia site for CoA and CoD only, indicated by *.

DISCUSSION

The purpose of this cross-sectional study was to compare bone density and strength outcomes between collegiate female swimmers and age-matched sedentary controls. We hypothesized that bone density among collegiate swimmers would be greater at the humerus, hip, and radius when compared to a sedentary control group. Our results did not support this hypothesis. However, our results supported our hypothesis that pQCT-measured bone outcomes, such as cortical area (CoA) and cortical density (CoD) at the proximal tibia, would be significantly lower in the swim group compared to controls. We discuss aspects of these results below.

We found no significant differences in DXA-derived bone density outcomes between collegiate swimmers and sedentary age-matched controls at the hip or radius. These results are consistent with existing research showing either lower or no difference in aBMD between swimmers and control populations at comparable measured sites (4, 14, 16, 17, 18), suggesting no osteogenic effect of swimming on aBMD at clinically relevant skeletal sites. As an example, Taaffe et al. found that femoral neck aBMD of both collegiate female gymnasts ($1.117 g/cm^2$) and age-matched non-athlete controls ($0.974/cm^2$) was significantly higher than swimmers ($0.875 g/cm^2$) (17). Swimmers in the present study reported spending nearly 14 hours per week in pool training, which is less than the 22 hours of swim training by collegiate athletes per week reported by Taaffe (17), but consistent with studies reporting ranges of 10 – 13.5 hours per week (5, 14). Swimmers in the present study reported competitive swim training for an average of 11.89 years prior to data collection, which is comparable to the findings by Taaffe and others showing that swimmers begin sport-specific training in early adolescence (17), and may prefentially engage in swimming over weight-bearing sports. Nonathlete controls may have undergone everyday loading over this same period of time, subjecting them to more weight-bearing strains on the skeleton, resulting in comparable bone density between swimmers and control populations (17, 18).

Consistent with our hypothesis, the present study showed significantly lower midshaft (66% site) tibia pQCT-derived vBMD and bone area outcomes in swimmers compared to controls. At the tibia, cortical vBMD and cortical bone area were 6.0% and 13.8% lower, respectively, than controls. Similarly, Nikander et al. showed significantly lower midshaft tibia cortical thickness and bone mineral content in swimmers compared other athletes in other sports (running, volleyball, soccer, racquetball) and a sedentary control group, suggesting that the lack of weight-bearing forces provides inadequate stresses to induce increases in bone mass or adaptations seen in other athletes (14). Even among female swimmers (ages 12-18) who concurrently or previously engaged in weight-bearing sports (average of 2 additional hours a week) in addition to swimming, Gómez-Bruton found no significant differences in lower extremity bone density compared to controls (5).

In the present study we predicted the humerus midshaft would have greater vBMD secondary to the muscular stresses exerted on the humerus during swimming. However, we found no significant group differences in vBMD, bone geometry, or density-weighted strength-strain index (SSI) outcomes. Despite no differences in vBMD, Nikander at al. found that swimmers had greater humerus midshaft polar section modulus, a geometry-based bone bending strength measure, compared to controls, but similar to soccer, volleyball, and racquet sport athletes, suggesting that the large muscles (biceps brachii, triceps brachii, and deltoid) inserting on the humeral shaft may have produced sufficient muscular contractions leading to more robust geometry resulting in higher bone strength (14).

Despite the lack of statistical significance in several bone outcomes, there were some parameters of which to take notice. The vBMD at the proximal (33%) radius was higher, although not significant, in swimmers compared to the control group. Oosthuyse et al. found significantly greater cortical and total bone area and strength strain index at the 65% radius in swimmers compared to controls, explained by repetitive muscular contractions and torsional bone strain due swimming patterns (15). Similar to the results of the present study, Gómez-Bruton et al. did not find significant differences in pQCT-derived bone parameters at the distal (4%) and proximal (66%) radius when comparing female swimmers to a control group. Together, these results suggest there are inconsistent effects of swimming on upper extremity bone density and strength parameters despite the constant use of the forearm to propel the body during swimming (5).

Few studies have performed HSA of DXA femoral neck scans to compare athlete groups to sedentary control groups, which provides an analysis of geometric parameters at the hip, indicating strength. HSA of DXA proximal femur scans in the present study showed no significant differences in CSMI, CSA, CT, or BR between swimmers and the control participants. These results are consistent with findings by Vlachopoulos and colleagues showing no significant differences in femoral neck cross-sectional area, cross-sectional moment of inertia, or hip strength index in male swimmers compared to athlete controls, which may be explained by the lack of difference between weight-bearing exercise and loading in the mechanical patterns of swimming (18).

When considering the mechanostat theory of bone adaptation, it may be reasonable to conclude that the weight-bearing tibia and femoral neck in swimmers develop less robust microarchitectural adaptations than athletes in weight-bearing sports and sedentary control groups. As a non-weight-bearing physical activity there may be less muscular strain at these regions to act as stimuli for osteogenesis. In addition to nearly 14 hours of pool training, swimmers in the present study also spent 3.6 hours per week engaged in resistance training, which may not have been enough to make up for high levels of swimming. It may also be that muscular contractions on bones are not sufficient stimuli to measurable bone adaptations in density and strength, providing evidence that ground reaction forces and weight-bearing exercise may be the primary mechanism for beneficial bone adaptations (17, 18). Furthermore, Schipilow and colleagues suggest there is a selection bias for swimming in individuals who genetically have a lower bone density (16). For this reason, swimmers may be more likely to maintain involvement in this sport, explaining the consistent finding of similar or lower bone density and strength at all anatomical locations as compared to controls and other athletes (16).

The recommended calcium intake for adolescents is 1300 mg per day, and the average intake of calcium was below that for both groups in the present study. Control participants consumed an average of 250 mg per day less than swimmers, which may not account for the lower bone density in swimmers. One study found that 60% of swimmers had low vitamin D levels, which is a necessary vitamin for increasing and maintaining bone health (1). These two factors in association could explain the lower bone strength and density in swimmers.

This study is strengthened by the analysis of bone strength and density using a combination of DXA and pQCT, particularly at the understudied midshaft humerus and narrow neck of the femur sites. This study also provides a more robust investigation of site-specific bone adaptation among female collegiate swimmers compare to those of a sedentary, non-athlete, age-matched control group which contributes important knowledge regarding the minimal to potentially detrimental osteogenic effect of swimming in both weight-bearing and non weight-bearing limbs in comparison to sedentary controls. Despite the significant findings at the proximal tibia, the sample size of this study may not have been large enough to detect significant differences of all bone outcomes. Also, the athletes studied participate in Division III competition, which requires less time commitment and year-round involvement, meaning it may not provide sufficient specialization to detect differences that may be found in an elite population as observed in previous studies.

Conclusion**:** This study is the first to evaluate the site-specific bone density, geometry, and strength outcomes in female collegiate swimmers in comparison to sedentary controls using DXA (including HSA outcomes) and pQCT. Our findings indicate that involvement in swimming for females was not associated with greater bone density and strength, but in fact may be disadvantageous in the lower leg. While swimming is an aerobically strenuous activity, it may not provide adequate muscular stresses necessary for stimulating bone microarchitectural strength and density adaptations. Along with previous research, our results suggest that weight-bearing exercises should be regularly performed as an osteogenic supplement to swimming for adolescent females. Finally, our results contribute to a growing body of evidence suggesting that significant differences in bone geometry and density between swimmers and a sedentary population may only be observed in the tibia. Future research should include larger samples sizes and athletes performing at an elite level who spend more time swimming year-round. Future studies could also investigate bone outcomes among individuals across the age spectrum who swim as their primary form of physical activity, which may better indicate the effects of swimming on bone adaptations throughout life.

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