

RESEARCH ARTICLE

Gluteal muscle damage leads to higher *in vivo* hip joint loads 3 months after total hip arthroplasty

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Abstract

Background

Total hip arthroplasty (THA) is in most cases improving patients' life quality immediately after surgery. However, a closer look at these patients, especially with modern gait analysis methods, reveals also negative consequences due to the surgical approach related injury to the pelvic muscles. We hypothesized that this damage will have a negative impact on hip joint contact forces during activities of daily living (ADL).

Methods

10 patients undergoing THA received an instrumented hip joint implant enabling real time *in vivo* measurements of hip joint loads using a direct lateral approach. Pre- and 3 months postoperative computed tomography (CT) scans were used for evaluation of the periarticular muscle status, using muscle volume, fat ratio and lean muscle volume as parameters. An analysis of *in vivo* hip contact forces was made 3 months after THA during ADL (walking, stair climbing, chair rising and sitting) and correlated with the morphology of the periarticular muscles.

Results

We found a significant decrease of volume by 25% (-3 to -45, $p = 0.005$) and increase in fat ratio of the Gluteus Minimus (Gmin), resulting in a decrease in lean muscle volume of 28% (-48 to 0, $p = 0.008$). This was accompanied by an inverse development in the Tensor Fasciae Latae (TFL) resulting in a lean muscle volume increase of 34% (-2 to -102, $p = 0.013$). Changes in Gluteus Medius (Gmed) and Gluteus Maximus (Gmax) have not been observed in the short-term follow up. A decreased Gmin lean muscle volume was found to strongly correlate with high *in vivo* joint contact forces in all tested ADL.

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Conclusion

The decrease of Gmin volume can be seen as a direct effect of THA surgery, whereas the increase of TFL might compensate for loss of Gmin volume. Lean muscle volume and fat ratio were better predictors for joint contact forces than total muscle volume. These effects were most pronounced during sitting down and standing up due to the higher demand on the gluteal muscles during these activities.

Introduction

In Germany, more than 200 000 total hip arthroplasties (THA) are performed per year [1]. THA can increase quality of life and mobility [2], yet it can also lead to negative consequences. These negative effects can be related to the surgical approach and include atrophy, fatty degeneration and loss of function in the hip surrounding muscles [3,4], which in return influences general functionality and mobility of the patient. Both, atrophy and fatty degeneration, have been shown to negatively influence the postoperative outcome [5–7]. In studies investigating muscle or tendon repair of the shoulder and hip, fatty degeneration has been shown to negatively impact the functional outcome and muscle strength [5]. An increase in the fatty degeneration of the gluteal muscles is often associated with impaired walking patterns and other ADL such as chair rising [8]. An abnormal gait pattern, such as the Trendelenburg gait, can cause higher *in vivo* joint contact forces [9,10] which can be a potential harm to implant longevity [11].

The gluteal muscles, along with the TFL, play a central role in stabilizing the hip joint in most ADL [12–18], a damage can thus entail serious negative consequences [19]. Whereas joint contact forces are influenced by muscle status, implantation angle and lever arm of contributing muscles [16,20,21], the periarticular muscles of the hip determine up to 95% of the joint contact forces during walking [14].

Using the direct lateral approach (DLA), a widely performed THA approach [22–24], gluteal muscle damage is inevitable for good exposure of the joint [25] with the aforementioned patient risks, including abnormal postoperative gait patterns. Prior research has indicated the possibility, that a damage to periarticular muscles lead to increased joint contact forces [16,26], however, to our best knowledge, there are no *in vivo* studies that correlate the hip muscle status with joint contact forces. Most analyses of the impact of muscle status on joint contact forces address gait patterns or ground reaction forces and can only extrapolate on joint forces [27]. This study aims at investigating the influence of the periarticular hip muscle status on the joint contact forces in THA patients 3 months after surgery. Based on previous research we hypothesized that an impaired gluteal muscle status will correlate with higher *in vivo* joint contact forces in the hip.

Methods

Subjects and study design

We retrospectively analyzed individual *in vivo* measured hip joint loading and muscle status. All patients were operated using the direct lateral approach ($n = 10$, mean age 57.3 years, 50 to 68, female: $n = 2$, Table 1) and received an instrumented hip implant ([28]). The study was approved by the Charité Ethics committee (EA2/057/09) and registered at the ‘German Clinical Trials Register’ (DRKS00000563). All patients gave written informed consent prior to participating in this study.

Table 1. Demographic characteristics of patient collective 3 months after THA.

Subject	H1L	H2R	H3L	H4L	H5L	H6R	H7R	H8L	H9L	H10R
Age [years]	56	61	60	50	63	68	53	55	54	53
BMI [kg/m ²]	24	27	31	25	31	27	28	25	34	37
Sex [f / m]	m	m	m	m	f	m	m	m	m	f

BMI = Body Mass Index, R = right operated side, L = left operated side.

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Computed tomography (CT)

All patients were scanned using helical CT (Toshiba Aquilion ONE, V4.61GR004, Tokyo, Japan; 120kV, 200mAs, FOV 40cm). Original CT scans were reconstructed to 5mm files (GE Medical systems, software version vxtl_12.3–2.86, volume viewer, smooth 1 filter). CT scans were obtained one day prior to and three months after surgery.

Image analysis

Using dedicated software (Osirix Imaging Software, Geneva Switzerland; Amira Visage Imaging, Berlin, Germany) for CT analysis, muscle slices with 5 mm distance were manually outlined and intermediate surface completed using interpolation. To control for variation in patient body heights, volumes were measured between the anatomic landmarks of the fourth lumbar vertebrae (L4) and the lesser trochanter (LT). Muscular fatty degeneration was assessed using a standardized Hounsfield Unit (HU)–based approach [8,29]. For the gluteal muscles, three consecutive slices were selected for analysis starting 3 cm cranial of the greater trochanter (GT) as a reproducible anatomic landmark. The TFL was measured in three consecutive slices inferior to the superior anatomical aspect of the GT.

In vivo load measurement

In vivo joint contact loads were collected using instrumented hip implants, a detailed description of the prostheses has been previously published by Damm et al. [28]. The following ADL were included in our protocol: level walking (self-chosen speed by the patients), stair climbing without support, chair sitting and rising. The resultant force (F_{res}) was calculated from the force vectors F_x , F_y and F_z , which respectively act in the lateral, anterior and superior direction of axis of the femur. F_{res} are reported in Newton (N) and percentage body weight (%BW). Periarticular muscles are active during specific time points in the activity cycle. Hence, each periarticular muscle influences the movement and actions during gait cycle differently [12–18]. For the appropriate correlations between muscle status and joint contact forces we searched during which peak each periarticular muscle is active in the ADL activities (see Table 2). This enabled us to identify which muscle damage could have an impact on joint contact forces.

Table 2. Activity pattern of the ipsilateral hip muscles at defined time points of the joint loads (shown in Fig 1).

ADL	Gluteus minimus	Gluteus medius	Gluteus maximus	TFL
Walking 1 Peak	+	+	+	+
Walking 2 Peak	+	+	-	-
Stairs up 1 Peak	+	+	+	+
Stairs Down 1 Peak	+	+	+	+
Sit Down Max	+	+	+	+
Stand up Max	+	+	+	+

active = +, not active = -

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Statistical methods

The Mann-Whitney U test was used for testing for inter-individual, and Wilcoxon’s test for intra-individual differences in pre- and postoperative muscle volume and fat ratio. Correlations between volume and fat ratio of a muscle and *vivo* joint loads were analyzed with the use of the two tailed Spearman rank test. Statistical analyses were performed using IBM SPSS (SPSS, 2013), $p < 0.05$ was considered significant.

Results

Muscle status

Three months postoperative changes, compared to preoperative values, of volumes and fat ratio are displayed in Table 3. Total volume of the Gmin muscle decreased by 25% (-45 to -3, $p = 0.005$), which was accompanied by a non-significant increase of total TFL volume by 14% (-10 to 56, $p = 0.059$).

Lean volume of the Gmin muscle decreased by 28% (-48 to 0, $p = 0.008$), Gmed and Gmax showed minor, insignificant changes and TFL lean volume increased by 34% (-2 to 102, $p = 0.013$).

The indicator of fatty degeneration, fat ratio, was found to be increased in all gluteal muscles, but lacked significance (Gmin $p = 0.169$, Gmed $p = 0.445$, Gmax $p = 0.475$). The TFL showed a substantial decrease in fat ratio of 57% (-98 to -11, $p = 0.017$).

Joint contact forces

Inter-individual differences of peak forces were relatively small in walking and stair climbing, but showed large differences between patients during sitting down and standing up (Fig 1 and Table 4). The overall highest loads were observed during stair descend, with average peak forces of 281%BW (198–418) at the 1st peak. The lowest peak forces were measured during sitting down, with an average of 169%BW (109–277). Patient H5 reached the highest single peak forces during almost every exercise, which was most pronounced in stair negotiation (336% BW in ascent; 418%BW in descent).

Correlation between muscle status and joint contact forces

Total muscle volume showed, beside Gmed volume ($r_s = 0.67$, $p = 0.003$) with walking 1st Peak, no significant correlations with joint contact forces.

However, a decreased lean muscle volume of the Gmin showed strong correlations with higher contact forces in all exercises ($r_s = -0.67$ - -0.94 , $p = 0.035$ – 0.005). Lean muscle volume of the other hip muscles did not correlate significantly with the joint contact forces (see

Table 3. Mean postoperative volume of the ipsilateral side in [%].

Muscle	Gmin	Gmed	Gmax	TFL
Total muscle volume	-25 (15.3)**	6 (12.5)	-2 (9.8)	14 (21.9)
Lean muscle volume	-28 (14.4)**	3 (15.1)	-9 (21.8)	34 (31.2)**
Fat volume	-2 (42.7)	48 (112.0)	31 (94.3)	-52 (36.8)*
Fat ratio	32(56.8)	36 (96.4)	31 (80.8)	-57 (32.1)*

SD = standard deviation, significance level

** = 0.01

* = 0.05

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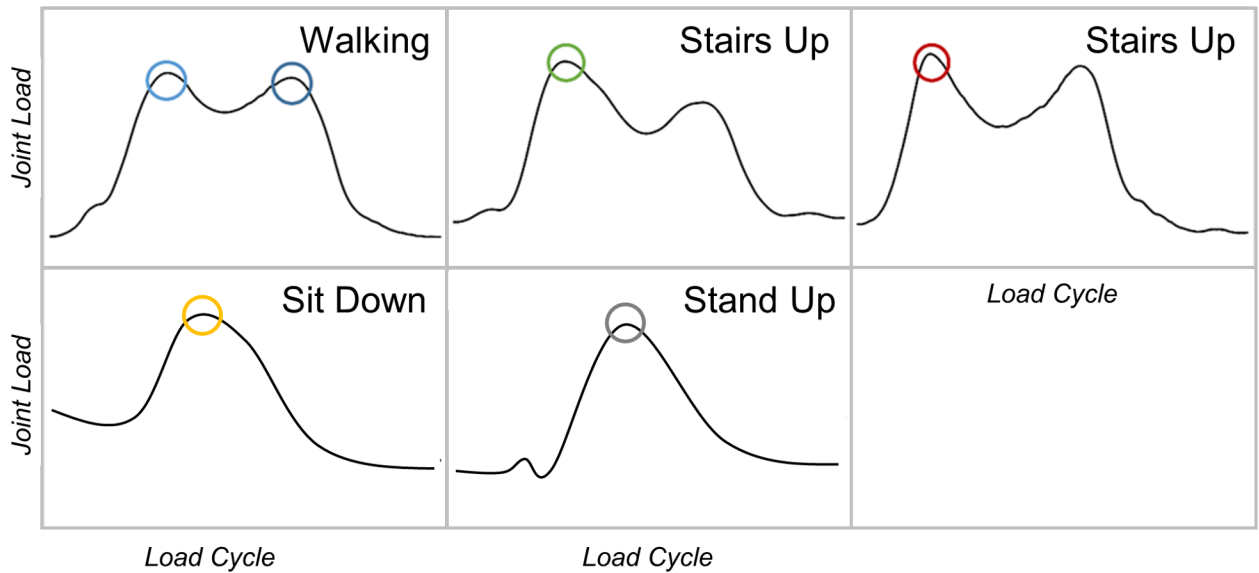


Fig 1. Average load patterns of in vivo measured hip joint contact forces during different ADL. Indicated are investigated peak values in all patients.

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Table 5). A lower lean volume of the GMax, however, showed a trend to correlate with higher contact forces in sitting down ($r_s = -0.71$, $p = 0.11$).

Fat ratio showed strong correlations between all gluteal muscles and forces during sitting down (Gmin $r_s = 0.93$, $p = 0.008$; Gmed $r_s = 0.94$, $p = 0.005$; Gmax $r_s = 0.84$, $p = 0.036$) and standing up (Gmin $r_s = 0.84$, $p = 0.036$; Gmed $r_s = 0.89$, $p = 0.019$; Gmax $r_s = 0.75$, $p = 0.08$). The fat ratio of the Gmed, Gmax and TFL were further shown to correlate with 2nd peak walking joint contact forces ($r_s = 0.65$ – 0.73 , $p = 0.042$ – 0.018) (Table 6).

Table 4. Individual contact forces and load cycles during sit down / stand up at 3M after THA in [%BW (N)].

Patient	H1L	H2R	H3L	H4L	H5L	H6R	H7R	H8L	H9L	H10R	Average (SD)
3M											
Walking	225	230	209	249	294	246	293	301	275	228	255 (33)
1 P	[1679]	[1808]	[1841]	[1950]	[1530]	[2044]	[2634]	[2346]	[3044]	[2197]	[2209(429)]
Walking	221	250	217	234	270	224	228	288	217	235	238 (24)
2 P	[1666]	[1959]	[1915]	[1829]	[2326]	[1860]	[2045]	[2241]	[2408]	[2260]	[2051(246)]
Stairs Up	200	252	212	303	336	254	266	304	283	263	267 (42)
1 P	[1509]	[1976]	[1871]	[2373]	[2896]	[2111]	[2395]	[2372]	[3135]	[2535]	[2317(480)]
Stairs Up	172	224	204	190	324	237	222	291	200	268	233 (48)
2 P	[1294]	[1756]	[1799]	[1491]	[2794]	[1970]	[1994]	[2269]	[2218]	[2386]	[1997(442)]
Stairs Down	217	246	198	325	418	298	253	299	273	282	281 (62)
1 P	[1635]	[1933]	[1745]	[2548]	[3604]	[2477]	[2272]	[2328]	[3029]	[2722]	[2429(598)]
Stairs Down	192	233	250	249	388	243	233	300	218	253	256 (54)
2 P	[1450]	[1450]	[2202]	[1947]	[3344]	[2020]	[2099]	[2338]	[2394]	[2437]	[2206(498)]
Sit Down	109	154	116	145	277	NA	NA	NA	NA	212	169 (64)
Max	[819]	[1208]	[1004]	[1158]	[2387]					[2044]	[819(628)]
Stand Up	103	151	130	192	355	NA	NA	NA	NA	238	195 (92)
Max	[776]	[1183]	[1127]	[1158]	[2387]					[2291]	[1487(677)]

SD = standard deviation, NA = not available

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Table 5. Correlation of ipsilateral lean volume in [cm³] and *in vivo* joint contact forces in [N] at 3 months.

	Ipsilateral	Gluteus Minimus	Gluteus Medius	Gluteus Maximus	TFL
3M	Walking 1 P	$r_s = -0.67^*$ (0.035)	$r_s = 0.24$ (0.51)	$r_s = 0.30$ (0.41)	$r_s = 0.47$ (0.17)
	Walking 2 P	$r_s = -0.75^{**}$ (0.013)	$r_s = -0.08$ (0.83)	$r_s = -0.02$ (0.96)	$r_s = 0.41$ (0.24)
	Stairs Up 1 P	$r_s = -0.82^{**}$ (0.004)	$r_s = 0.02$ (0.96)	$r_s = 0.07$ (0.86)	$r_s = 0.10$ (0.78)
	Stairs Down 1 P	$r_s = -0.61$ (0.06)	$r_s = -0.18$ (0.63)	$r_s = -0.24$ (0.51)	$r_s = -0.04$ (0.91)
	Sit Down Max	$r_s = -0.94^{**}$ (0.005)	$r_s = -0.66$ (0.16)	$r_s = -0.71$ (0.11)	$r_s = -0.14$ (0.79)
	Stand Up Max	$r_s = -0.89^{**}$ (0.019)	$r_s = -0.49$ (0.33)	$r_s = -0.60$ (0.21)	$r_s = 0.09$ (0.87)

r_s (p-values) calculated using Spearman’s rank correlation, significance level

** = 0.01

* = 0.05; P = Peak

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Discussion

This study aimed at investigating the relationship between hip muscle status and *in vivo* hip joint contact forces after THA. To our knowledge, this is the first study worldwide comparing the individual hip muscle status and the *in vivo* measured joint contact forces. Our results generally support our hypothesis that an impaired muscle status, determined by muscle atrophy and fatty degeneration, corresponds with higher *in vivo* joint contact forces. In contrast to our expectations, total muscle volume was not related, but lean volume and fat ratio of periarticular muscles showed stronger correlations with an increase of *in vivo* joint contact forces. This effect was most pronounced for the Gmin muscle. Out of all analyzed activities, fat ratio and joint contact forces were best correlated during sitting down and standing up in all gluteal muscles. The TFL failed to show any relation between the muscle status and joint contact forces, despite its notable changes from pre- to postoperative.

The peak forces measured in our study are comparable to those described in the literature and are a good representation of normal joint contact forces in daily life^{9,26}. Three months after THA we found a decrease in the ipsilateral Gmin muscle volume, which has previously been described in the literature [30–33]. This decrease reflects direct muscle damage inherent to the lateral approach, a partial or complete detachment of the Gmin muscle playing a role in the mechanism of injury [34]. However, the contralateral decrease in lean volume indicates that not only direct damage can result in a loss of this important hip stabilizer.

The hypertrophy of ipsilateral TFL was a finding, that also confirms previous analyses of patients receiving THA via a direct lateral approach, and has been ascribed to decreased gluteal muscle function due to damage associated with surgery[25,35,36]. The TFL is, together with

Table 6. Correlation of ipsilateral fat ratio in [%] and *in vivo* joint contact forces in [%BW] at 3 months.

	Ipsilateral	Gluteus Minimus	Gluteus Medius	Gluteus Maximus	TFL
3M	Walking 1 P	$r_s = 0.03$ (0.93)	$r_s = 0.31$ (0.39)	$r_s = 0.14$ (0.70)	$r_s = 0.09$ (0.80)
	Walking 2 P	$r_s = 0.20$ (0.58)	$r_s = 0.71^*$ (0.022)	$r_s = 0.73^*$ (0.018)	$r_s = 0.65^*$ (0.042)
	Stairs Up 1 P	$r_s = 0.20$ (0.59)	$r_s = 0.32$ (0.37)	$r_s = 0.18$ (0.63)	$r_s = 0.21$ (0.58)
	Stairs Down 1 P	$r_s = 0.05$ (0.89)	$r_s = 0.43$ (0.21)	$r_s = 0.39$ (0.27)	$r_s = 0.33$ (0.34)
	Sit Down Max	$r_s = 0.93^{**}$ (0.008)	$r_s = 0.94^{**}$ (0.005)	$r_s = 0.84^*$ (0.036)	$r_s = 0.14$ (0.79)
	Stand Up Max	$r_s = 0.84^*$ (0.036)	$r_s = 0.89^*$ (0.019)	$r_s = 0.75$ (0.08)	$r_s = 0.26$ (0.62)

r_s (p-values) calculated using Spearman’s rank correlation, significance level

** = 0.01

* = 0.05; P = Peak

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Gmin and Gmed, part of the hip abductor muscles and involved in stabilizing the hip joint during various movements[36]. Atrophy of one part of the abductor group can be compensated by hypertrophy of another. Furthermore, increased loading post surgery can also be a cause of the TFL hypertrophy[35]. TFL hypertrophy is most likely a compensatory mechanism for the loss of gluteus minimus.

We hypothesized that impaired muscle function would correspond with higher *in vivo* joint contact forces. For a controlled joint function, intact muscles are of utmost importance—with peaks in joint contact forces being one possible consequence of an uncontrolled contraction pattern due to muscle damage [37,38].

We initially considered the total muscle volume as sufficiently descriptive parameter for muscle status. Contrary to our considerations, total muscle volume and joint contact forces were only weakly correlated, underlining the need of qualitative parameters of muscle substance rather than un-corrected parameters when describing functional correlations. Gmin lean muscle volume, which is the volume of the muscle after deduction of the intramuscular fat, was strongly inversely correlated with joint contact forces. This suggests that lean muscle volume, and not total muscle volume, is a better predictor of muscle function, as lean muscle volume consists only of functional and contractile muscle tissue.

Besides muscle atrophy, we hypothesized that a higher fat ratio would also correspond with higher joint contact forces. Higher gluteal fat ratio can lead to an impaired gait cycle[8] and impaired gait cycles correspond with higher *in vivo* joint contact forces [9,10,39]. In the gluteal muscles, we observed a positive trend with higher fat ratios corresponding with higher joint contact forces. High fat ratio has been described to be a predictor of clinical surrogate of muscle function, possibly by the increasing stiffness of the muscle and thereby decreasing force[8] [40], apart from the accompanying loss of contractile muscle substance. The strongest correlation we observed was during standing up and sitting down. Although the joint contact forces are higher during stair walking, the physical demand on the gluteal muscles is higher during sitting down[41,42] where they act as hip stabilizers and extensors.

Other factors, besides muscle damage, can cause joint contact forces to increase. The contribution of other muscles that take over the function of impaired muscles could have influenced the joint contact forces. Bergmann et al.[26] described that various muscles with different angles at the hip joint may cause the increase in joint contact forces [9]. Since muscles make up 50–90% of the *in vivo* acting joint loading, the changes in muscle status will be of great importance.

Although Gmin is presumed to have less influence on the body balance than Gmed [14,18], we observed that loss of Gmin muscle resulted in higher forces in the hip joint. The significant correlation of Gmin lean muscle volume and fat ratio with higher contact forces might indicate that the Gmin plays a more important role in stabilizing the hip during sitting down and standing up than expected [14,18]. Literature about Gmin activation and precise function is scarce. To our best knowledge, only one study investigated Gmin separately using electromyography [18] and its action during walking. Other studies analyzed the combination of Gmin and Gmed [31].

Little is known about the exact contribution of the Gmin in daily activities, so its activation might be different than that of the Gmed during stair climbing or descending[12,14,18]. The relation we found during walking and stair climbing might give an insight of the function of Gmin, describing its important role during these activities.

Limitations of our study design

This study has several limitations. First, our study cohort consists of ten patients, which is too small to draw firm conclusions. Second, *in vivo* joint loading information from the preoperative situation was not available. It is possible that the loads stayed the same while muscle status

changed. In our study, we focused on a short-term follow up after THA. We have reason to believe, that within the first 3 postoperative months period the most pronounced changes in the periarticular musculature take place, since muscle regeneration will to the largest extent be completed within this time frame. Nevertheless, future research will also analyze long-term data, following the question if a post-injury reorganization of the periarticular musculature leads to changes in the relation of muscle status and contact forces. Future studies should also assess clinical outcome data, which we did not do in this study. This might give a better insight in the clinical consequences of the elevation of hip contact forces due to muscle damage. Finally, we only presented data for the ipsilateral side. Although contralateral gluteal muscles also contribute to ipsilateral joint contact force, they only contribute up to a maximum of 15% of joint contact forces [12].

Conclusion

These results contribute to knowledge of understanding the influence of muscle damage on joint contact loads. The hypertrophy of the TFL showed that a compensation mechanism exists for the hip abductor group after initial gluteal muscle damage. The lack of correlation of total muscle volume and the evident correlation of fat ratio and lean muscle volume shows, that, when assessing post-THA recovery, no reliable assumptions can be made on the total muscle volume regarding joint contact forces.

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