

# Mechanical Design of a Robotic Exoskeleton for Upper Limb Rehabilitation

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**Abstract.** This work presents the conceptual design, construction and testing of an upper limb rehabilitation system consisting of an exoskeleton of 6 degrees of freedom and a Human Machine Interface (HMI) to configure and control the exoskeleton. We present the study of the kinematics of the mechanical device followed by a three-dimensional modeling. Before the design of the exoskeleton was finished, we proceeded to the construction of a prototype in order to validate the model, using the Fused Filament Fabrication (FFF) technology and a three RX-64 Dynamixel motors from Robotis. LabVIEW® software from National Instruments was chosen to develop the HMI to communicate the exoskeleton with a computer for control the device and obtain relevant data, as the position or movement velocity. The results show the feasibility of the assistance of the robotic device in a rehabilitation processes.

## 1 Introduction

Nowadays we can find many applications of robotics in the medical field. However, we found few devices developed specifically to assist during the rehabilitation processes of musculoskeletal injuries of upper limb [1–3].

Rehabilitation therapies currently carried out by techniques that are imprecise. They are generic therapies that produce long-term results and require great personal effort by a specialist.

There has been an increase in musculoskeletal injuries of 45% between 1990 and 2010 in the worldwide population [4]. For these reasons and according to literature [5–7], a robotic exoskeleton could be a tool for rehabilitation specialists and also offer the patient a personalized and more intense process [8–10] with repeatability [11] and better short-term results [12, 13].

Medical literature differs in the number of degrees-of-freedom (DOF) that has the human upper limb. It is estimated that exist between 13 and 16 DOF. This quantity of movements is excessive to be mechanically addressed therefore, we simplify the design choosing the relevant DOF for a rehabilitation treatment of the human shoulder.

Complementing the other studies, we analysed the different technics and movements that take place during upper limb rehabilitation treatment. These are the movements that a healthy patient makes along the day, in order to cleaning and feeding itself.

We based our development on a previous works which presents a musculoskeletal model of the upper limb that allows some movements such as the elbow flexion/extension and shoulder abduction/adduction [14, 15], two of the basic movements of arm rehabilitation. The reliability of this musculoskeletal model has been proven through simulations, as shown in [16, 17]. In [15] can be found the results of the simulations of both movements for the case of a healthy subject and one with upper brachial plexus injury. The software platform used was the version 2.2 of the Musculoskeletal Modeling Software (MSMS). MSMS is a free software developed by the University of Southern California [18, 19], which incorporate different tools to perform animations and simulations of the biomechanical behavior of musculoskeletal models.

The aim of this work is to develop a system for upper limb rehabilitation that includes a mechanical device controlled by a software system, which has an integrated musculoskeletal model. The ultimate purpose is to provide a tool for the rehabilitation staff, which allows a more precise and controlled therapy, and create a record of the evolution of the patient. With this the patient rehabilitation process would be optimized.

## 2 Requirements Engineering

This section presents the device requirements imposed by the medical team based on their experience. They have placed special emphasis on work space, ergonomics, safety and adaptability.

Contrasting the information obtained from the position of the DOF with the movements analyzed in the rehabilitation treatment, we observed which are the most decisive joints. We consider as determinants, those joints that allowed us to reach most of the different rehabilitation movements. The result was that we reduced the DOF to six. The exoskeleton's shoulder has 3 DOF: flexion-extension, abduction-adduction and scapula elevation-depression. Three others DOF can be found in the arm: forearm pronation-supination, elbow flexion-extension and humeral rotation. It is necessary to have one actuator for each DOF of the exoskeleton, therefore the kinematic of this system will be the same as the human shoulder.

Before starting the development of the mechanical part of the exoskeleton, we need to consider some restrictions for the use of the device in a medical environment. These recommendations were provided by physicians of the Infanta Sofia Hospital in Madrid. As a first step, the exoskeleton does not be able to overtake the operating space area of a human shoulder, because this would cause serious injuries to the patient. Secondly, the device has to be mechanically adaptable to the different human anatomies. This fact

determines the target group that could use the exoskeleton. In our development, we are considering to make a rehabilitation system for adults.

In addition, the exoskeleton has to be comfortable, because patients will use the device many hours per week. If the device causes some kind of discomfort in the patient, they will reject their use and the therapy will not be effective.

We also have to consider the materials to use, the geometry or the presence of annoying noises. The chosen material was aluminum, a commonly material used in medical devices because it provides a good mechanical behaviour with a low weight. In addition, aluminum does not cause interference with other medical devices.

Other important point is that the exoskeleton should have suitable dimensions for its use in hospitals, being better to have a reduced design.

### 3 Mechanical Design

For the development of the exoskeleton, we estimate the torques needed in each joint. To obtain the torques we calculate the weight of a human arm of a 100 kg person, based on [20]. The results of this analysis were that each joint has a different torque. However, we could appreciate that the 3 DOF of the shoulder need a considerably higher torque than the rest, so in order to reduce the final application cost, we considered to use two types of motor size.

We chose motors with a higher torque for the shoulder abduction-adduction, flexion-extension and the scapula elevation-depression. These motors were located in a tower behind the patient and thus reducing the weight of the exoskeleton and simplify the structure. In addition, the position of the motors shift the centre of gravity of the structure providing a greater stability. Another advantage is that the motor noises and vibrations are reduced, and this point is important to not affect the concentration of the patient. However, to obtain these results we have to design a transmission system to communicate the motors with the exoskeleton joints.

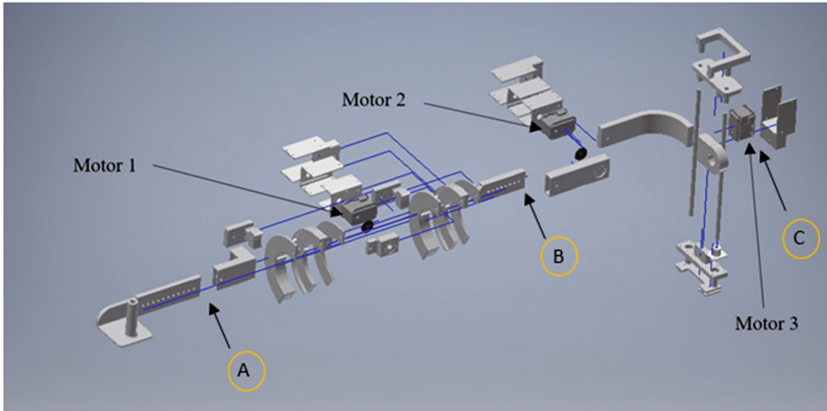
The motors with a lower torque was attached in the robotic arm directly and they enable the elbow flexion-extension, arm internal-external rotation and forearm pronation-supination.

To carry out this work, we had three Dynamixel RX-64 servomotors, which characteristics are specified in [21], therefore we decided to actuate the three more important joints: the elbow flexion-extension, shoulder abduction-adduction and shoulder flexion-extension. We also decided to exclude the transmission system, because it would complicate the design stage, and with three motors the global weight wouldn't be high. These joints are the most relevant because they allow us to move the arm in a tridimensional space. The other three movements are executed in a passive mode, in order to show the exoskeleton workspace.

The next step was to design a virtual modelling of the mechanical system. We used the software Autodesk Inventor Professional 2016® to develop the three-dimensional (3D) model, taking into account the medical restrictions previously mentioned.

The device adaptability is achieved with movable parts in the forearm and in the arm of the exoskeleton. The exploded view of the mechanism is showed in Fig. 1. It has

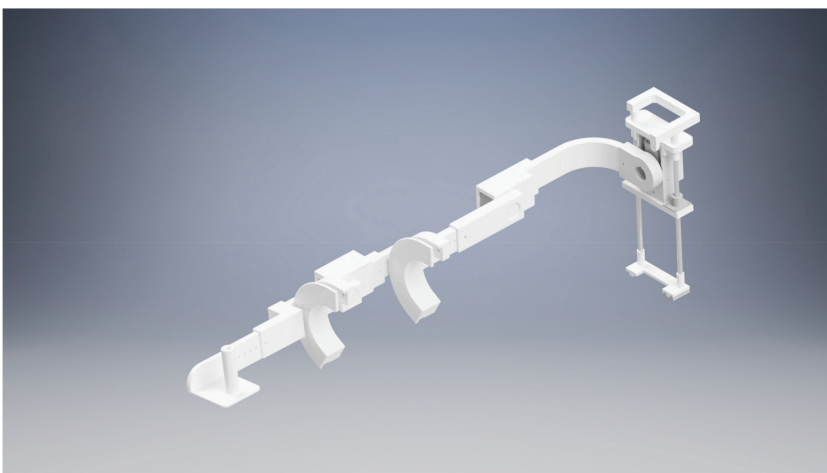
different position point that are manually fixed with a screw, indicated with parts A and B of Fig. 1. The adjustments of the lengths must be in the range of the patient's dimensions. In addition, we use the motor of the scapula to adjust the height of the patient, as is shown in part C of Fig. 1.



**Fig. 1.** Exoskeleton exploded view. Part A: adjustment of the forearm. Part B: adjustment of the arm. Part C: adjustment of the shoulder height

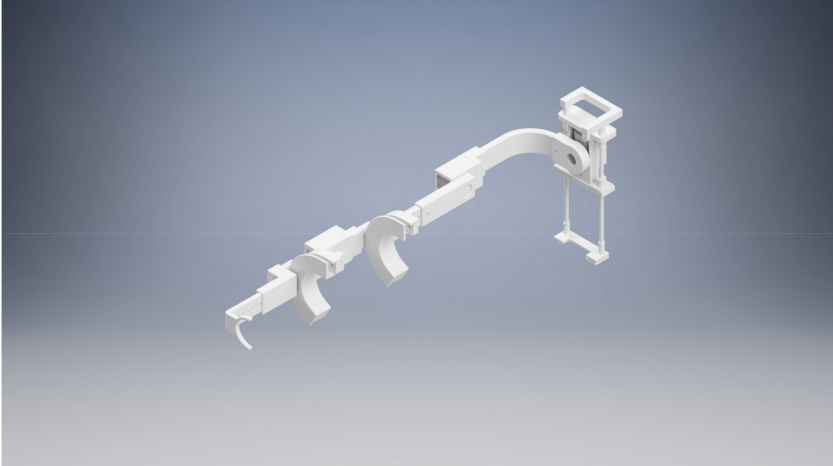
Furthermore, in Fig. 1 it is represented the three motors position that will move the actuated parts.

Other important aspects can be seen in Fig. 2. The final effector has a convenient form for the hand grip, the main idea is to have a support which can accurately guide the rotation during the pronation-supination movement. In addition, we developed another hand grip showed in Fig. 3. This element has an elliptical form, to connect the



**Fig. 2.** Three-dimensional model of the exoskeleton

patient's hand with the exoskeleton. This union allows us to control the hand position in the space and leave it free in order to endow the patients with hand mobility. The advantage of this system is to give the patient the ability to interact with objects in the environment. This increases the available exercises in rehabilitation therapies.



**Fig. 3.** Three-dimensional model of the exoskeleton with alternative hand grip

The following remarkable element was one of the most difficult to modelling and reproduce: the forearm rotation and the humeral rotation. This element was created due to the fact that rotational axes of pronation-supination and humeral rotation are coincident with the axes of the bones. This fact determine that we have to place the motors outside the axes. In order to solve this problem, we developed a semicircular piece with an internal track. This element is situated around the arm and the forearm and place the rotation motors axes in the joint arm axes. Finally, we approximate the scapula elevation as a shoulder rotation combined with a vertical displacement and this fact, allows us to simulate the vertical movement with two vertical guides. These will serve to adjust the height of the device to different anatomies.

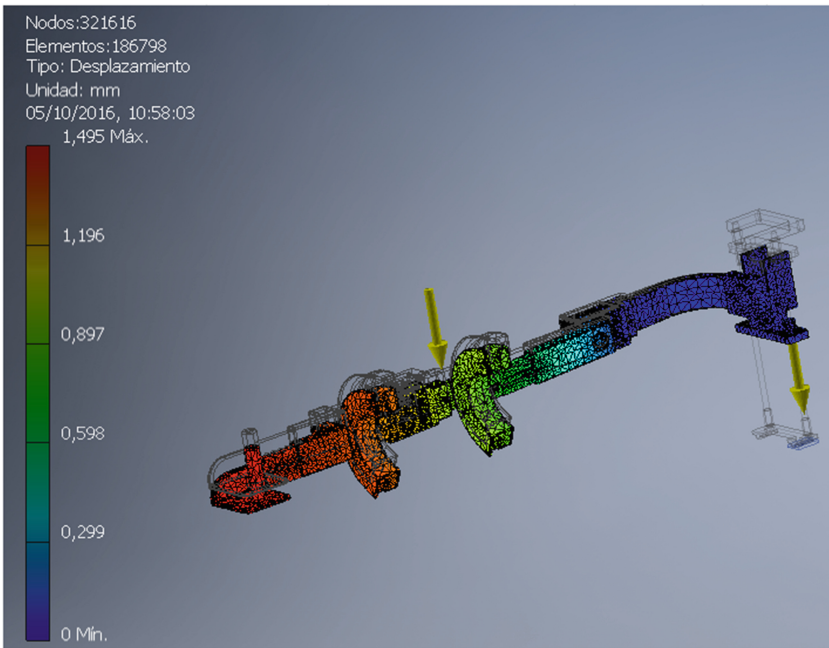
Then we made simulations of the different rehabilitation therapy movements with the 3D model created in order to obtain the angular limitations. With these simulations, we can demonstrate that the model could make one of the most difficult movement to achieve with an exoskeleton: take the patient's hand to the back, in internal rotation. To reach this complex movement is necessary to rotate all the joints of the device, which is part of the last phase of the rehabilitation therapy. The exoskeleton can achieve the range of motions showed in Table 1.

The 3D model was mechanically analyzed. We made a static simulation to calculate the structure with the finite element method (FEM). This test considered the material used as aluminum 6061, and this will be the material used in a next stage of the exoskeleton.

**Table 1.** Range of motion

Joint	Minimum angle (degrees)	Maximum angle (degrees)
Forearm prone-supination	-75°	75°
Elbow flexion	0°	135°
Humeral rotation	-75°	75°
Shoulder extension	0°	50°
Shoulder flexion	0°	180°
Shoulder abduction-adduction	0°	90°

In Fig. 4 is shown the displacement of the exoskeleton when we apply one force of 60 Nm in the middle of the robot arm. This force represents the weight of a human arm for a subject of 100 kg of weight. In addition, we contemplate the gravity value as  $11.2 \text{ m/s}^2$ . This is because we have considered that the exoskeleton could cover 0.6 m of distance during one second, so if the exoskeleton has no velocity, the acceleration produced in the movement is  $1.2 \text{ m/s}^2$ , and considering the gravity force as  $10 \text{ m/s}^2$  the sum of both is  $11.2 \text{ m/s}^2$ .



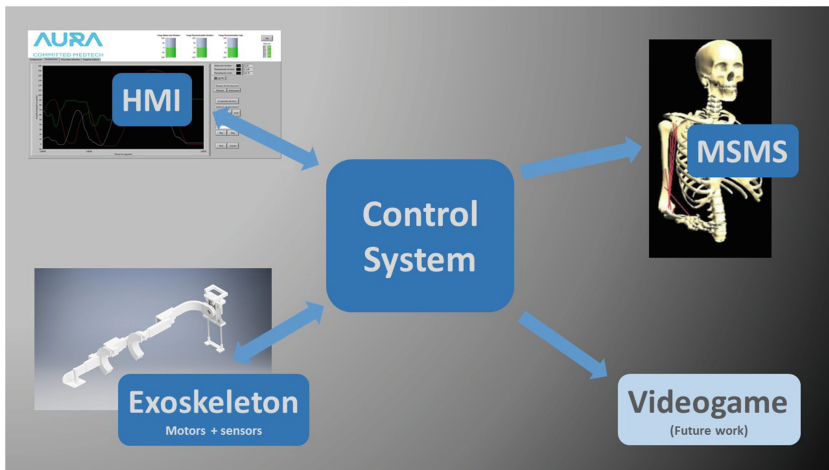
**Fig. 4.** Analysis of the 3D model by FEM method

The chosen position of the exoskeleton is the worst position from the point of view of the efforts, because the generated torque is higher. With this analysis, also we got the security coefficient of the structure, which is higher than 2 in the worst condition.

## 4 Experimental Results

### 4.1 Software Control Architecture

A software architecture was developed to interrelate the different elements of the system: the exoskeleton, a musculoskeletal model, the control system and the human machine interface (HMI). A diagram of the software system and the relationship between its elements it is shown in Fig. 5. The main objective was to obtain a robust, fast and modular system in order to obtain optimal results in the integration and a proper operation of the device.



**Fig. 5.** Software architecture to control the exoskeleton

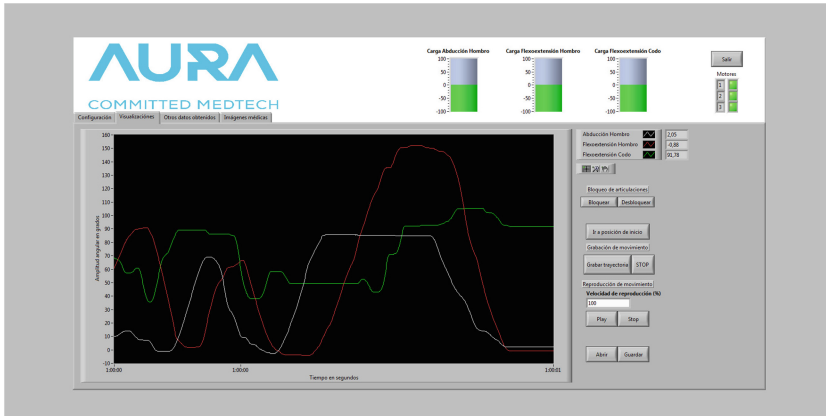
For the development of the control software and HMI, we chose NI LabVIEW®, and the reasons was based on the capacity and robustness of this platform, as well as powerful tools offered in relation with the user interface.

Communication with servomotors that integrates the exoskeleton has been carried out by serial RS-485 port, allowing bidirectional communication to read the angular position data of the motors, applied load torque exerted, errors and send set points of motion and configurations parameters.

Communication with the musculoskeletal model of the upper limb developed with MSMS [14, 15], is performed by User Datagram Protocol (UDP) communication. The model can reproduce the movement patterns collected from the patient or a therapy movement introduced by the rehabilitation specialist.

The control system governing the robotic exoskeleton is designed as a first stage in a simple and functional way, with the idea of implementing more functionality in the future, taking into account the feedback from medical specialists when they use this prototype.

The user interface has been made taking into account the characteristics of the end user, which are a medical staff with biomedical training. We consulted many professionals in the medical field and defined the main features and functionalities they need for this type of device, in order to facilitate their incorporation in hospitals and rehabilitation clinics. In Fig. 6 we can observe the appearance of the user interface.



**Fig. 6.** Human Machine Interface of the control system software

The principal objective during the development of this application has been to combine in a single system the control and management that the user needs to configure the robotic exoskeleton. Other important aspect of the HMI is the data collection for the posterior interpretation and storage in order to have the temporal evolution of the patient.

We have designed a HMI with a main screen session configuration in which they are declared the gender, mass and height of the patient, we can establish joint limits for patients with limited mobility and can also generate a rehabilitation routine with the desired configuration. On a second tab, we can see a graph with the joint positions, as well as tools for managing the exoskeleton as the beginning of therapy, stop, recording movements, load or save a data file, and select between active and passive mode functioning, as is shown in Fig. 6.

Once completed the mechanical development of the device and the associated software system, we proceed to the construction of a first prototype to validate it.

## 4.2 Practical Results

The prototype showed in this work was manufactured with the Fused Filament Fabrication (FFF) technology. The reasons are that is a low-cost technology, with a fast implementation and it allows to make complex geometries. The chosen material was Acrylonitrile butadiene styrene (ABS) due to the fact that has a better behavior with flexion efforts. Regarding the motorization of the device, we have decided to integrate the Dynamixel RX-64 servomotors of Robotis manufacturer. The reliability of these servomotors has been proven repeatedly through simulations, as shown in [22, 23].



Once completed the construction of the prototype, we proceed to integrate the software application to perform validation testing system. These operations consist of recording the movements of rehabilitation therapy performed by a subject, generating a file with all the data produced by the dynamics of the movement. Moreover, we can load a data file in order to reproduced defined exercise. In Fig. 7 we can observe the system reproducing a previous defined movement.

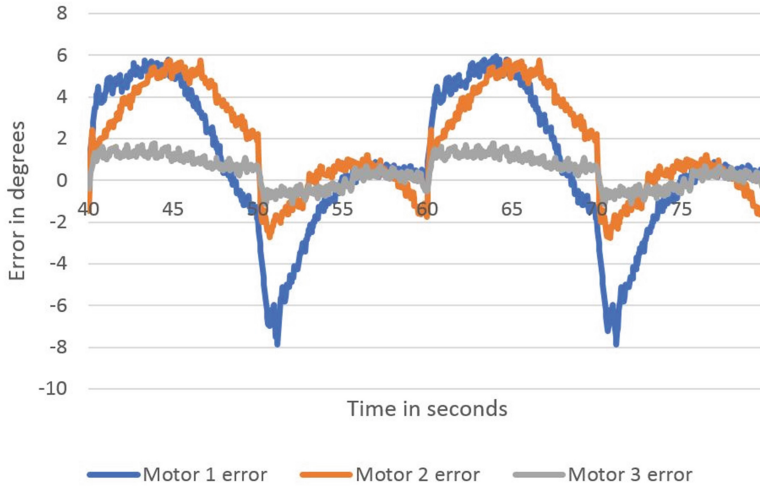


**Fig. 7.** Testing process of the prototype of the rehabilitation system

The results of the FEM analysis show that the require torque in every joint of the exoskeleton is higher than the torque generated by the Dynamixel motors. This fact determines that the motors cannot be used in the final device, because the system request others with a better torque characteristics.

Making the same analysis without the arm force and changing the material to ABS, we calculate the torque needed in the prototype. The conclusion of this analysis is that the Dynamixel can be used to move the prototype, but not the human arm combined with the exoskeleton.

Once the tests with different subjects was carry out, we found that the prototype reaches the required angular ranges, complying with medical restrictions. As we calculated, the prototype in ABS has had a good performance against the efforts required in the exercises. In addition, it has been proven to reproduce a path entered through a data file and has been shown to faithfully execute it according to the established control configuration, as is shown in Fig. 8.



**Fig. 8.** Exoskeleton tracking error chart

## 5 Discussion

Having analyzed the results, we can say that the device reach the objectives. The mechanical system has properly responded to the expected movements as well as the software system gives accurate and necessary information, and provides the user with sufficient tools for handling the device. Therefore, the functionality of the rehabilitation system is demonstrated.

The prototype was tested with healthy human subjects. In this experiment, we confirmed the simulation results. The prototype could move itself without a human arm but it can't move both.

Among all the results we have obtained in the course of this work, we can highlight the confirmation that the material of the structure must be more resistant than ABS. Also, it has been found that the mechanical structure allows the user a natural and comfortable movement in all GDL, beside placing the driving shaft of the exoskeleton perfectly aligned with the upper limb joints, all with a reduced visual impact. The software system includes a stable communication and important user information is obtained. It also allows to save the record of the evolution of the patient and load a previously designed therapy.

In order to actuate the passive joint and starting working in the transmission system, we decided to design a transmission that could be yoke to the passive joints. The idea was to use the bike wires to reproduces the motor movement in the exoskeleton joints.

This wires has a semi rigid plastic jacket, this allow us to modify the length of the exoskeleton without losing wire strain. The problem was that the exoskeleton has a big quantity of movement. This fact force the wire jacket to bend, and make more difficult to move the exoskeleton joints, in other words, we are increasing the torque needed. For this reason, we decided not to use the transmission system.

We left three joints as passive and this issue would be treated in future works, transforming them in active joints.

## 6 Conclusion and Future Work

Once built a first prototype and made the relevant tests, it is demonstrated the feasibility of the assistance of a robotic exoskeleton in rehabilitation processes. The repetitive movements performed by the physiotherapist can be emulated by a robotic mechanism. This system provides a valuable and accurate information that allows to particularize the subject rehabilitation therapy, and create a record of the evolution.

As future work the system update is pending after receiving feedback from health workers and implement an adaptive control of the system. Also, the next prototype will be manufactured in aluminum and all of the joints will be actuated.

As a result of the work we have created an exoskeleton prototype that can be used to obtain data, to design a new version, like quantity of movements, mechanical and communication problems, kinematics limits, physicians feedback. In addition, the prototype can be used to reproduces some experiments in which we could get data of subjects, combined with different muscles measure techniques like electromyography.

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