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# Development of a Pneumatic Robotic System for Bilateral Upper Limb Interactive Training with Variable Resistance*

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**Abstract— This paper presents the development of a pneumatic robotic system for bilateral upper limb interactive training with variable resistance (resistance means force resistance here). This device can be adjusted to certain angle of inclination to enlarge its workspace. A motion module is designed to direct linear movement of two handles in parallel. The handle can be actively driven by human users with variable resistance that is realized through a pneumatic system. The pneumatic system mainly consists of pneumatic cylinders, throttle valves and electromagnetic valves, which allows for the resistance control of each motion module. Three work modes, including asynchronous, synchronous and independent movements, are implemented. A game was also developed to guide human users to do task-oriented bilateral training. Quantitative experiments were conducted in a lab environment to evaluate the variable resistance performance of the robotic system. Qualitative feedbacks were also obtained from each participant. Results show that the robotic system is able to deliver appropriate bilateral training with different levels of resistance. The majority of the participants gave a positive feedback in using this device.**

## I. Introduction

Stroke is the second leading cause for acquired disability in adults [1, 2]. A report [3] shows that the stroke is a costly disease from human, family and societal perspectives in the world. Every two seconds, someone in the world will have a stroke. In 2016, there were almost 14 million incidences of first-time strokes worldwide. In the UK, there are more than 100,000 strokes annually, almost 12 strokes every hour, including over 400 childhood strokes. There are over 1.2 million stroke survivors, and two thirds of them leave hospital with disabilities.

Upper-limb motor impairments are very common on stroke survivors [4]. In the past few decades, robot-assisted upper-limb rehabilitation techniques have advanced rapidly [5-8]. With respect to traditional physical therapy, robotic systems can provide more intensive training by increasing the number of repetitions than that a therapist could impose [9, 10].

A variety of upper-limb rehabilitation robots have been developed with experimental validation on human subjects. They can be divided into wearable exoskeletons and platform devices based on the structural design. Some examples of upper-limb robotic exoskeletons are the ARMin III [11], the Rehab-Exos exoskeleton [12], and the L-EXOS [13, 14]. In contrast, these robotic system, such as the MIT-MANUS [15] and the hCAAR [16], fall into the group of platform-based devices. Upper-limb rehabilitation robots can be also divided into unilateral or bilateral systems. Most of existing robotic devices are designed for unilateral training of human shoulder, elbow, wrist, and even fingers [15].

Bilateral upper limb training that stimulates coordinated movement of both arms is a new form of stroke rehabilitation. Evidences show that this kind of training method has great potential in improving the efficiency of stroke rehabilitation[17, 18], including muscle strength, FMA scores, daily functions, etc.

A common way to achieve bilateral training is based on master-slave control (or mirror control) by healthy limbs guiding impaired ones for specific tasks. Li, et al. [19] proposed a master-slave control on a robot to implement bilateral arm training. The healthy limb provides the corresponding force for the impaired limb. Similarly, for a hand robotic device, the master-slave control was developed by Rashedi, et al. [20] to achieve mirror-image motion pattern. More advanced, Trlep, et al. [21] presented an adaptive assistance control on a bimanual training system to adjust the contribution of the unaffected arm for reducing the load on the paretic arm. Trials on four chronic stroke patients showed that the subjects were able to apply forces with the paretic arm similar to the forces of the unaffected arm.

This paper aims to develop a new rehabilitation robot to deliver bilateral upper limb coordination and muscle strength training for stroke patients. This device is developed to work in an active mode with different levels of resistance. It does not rely on external power for actuation, which makes it have great potential for clinical applications due to enhanced training safety. This paper is organized as follows. Following the Introduction, the development of the bilateral robotic system is described with details, including the mechanical design, pneumatic

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design, electrical system, and interactive gaming. Then, experiments were conducted to evaluate the control performance of the resistance performance of the robot, as well as the whole robotic system for bilateral training. Conclusion is summarized lastly.

## II. Robot Development and Analysis

This section details the development of the bilateral robotic system, including mechanical design, pneumatic design, electric components, and an interactive game.

### A. Mechanical Design

The bilateral robot mechanically consists of three modules, as in Figure 1, including a base (A), an adjustment mechanism (B), and a motion mechanism (C) for bilateral training. The base is a wheeled frame used to support the adjustment unit and the motion mechanism. The motion module, as the most important part of this robotic system, is designed to deliver linear movement to each human arm. The adjustment module is installed between the base and the motion mechanism.

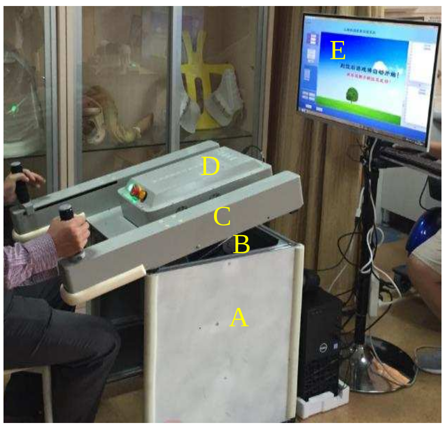



Figure 1. The bilateral robotic system. (A: Base, B: Adjustment unit, C: Motion mechanism, D: Control box, E: Computer screen)

The adjustment module is implemented through an electric telescopic rod that is mounted inside the base, as shown in Figure 2 (A). This allows the adjustment of the inclination (Ac) of the robot motion mechanism, ranging from 0° to 40°. Such posture adjustment of the motion module leads to a larger robot workspace for patients' upper limb rehabilitation training. It can be also adjusted to a specific angle depending on clinical needs of an individual, ensuring the training comfort and efficacy.

The motion module allows linear movement for each human arm, as shown in Figure 2 (B). During bilateral upper limb training, the participant is required to actively hold the handle, or passively fixed on it by straps if he/she does not have holding capacity.

Further in Figure 2 (B), the motion module can be divided into two sides (left and right) for bilateral training. They are same in function of linear movement for human arms. The distance (Sw) between two sides of the motion module could be adjusted manually, which allows for a larger workspace of this robotic system with flexibilities. Figure 2 (C) is presented to show the structure of each side, consisting of a base plate, a linear guide way, a slider, a pneumatic cylinder, a handle and the housing. The handle is fixed on the slider, driven to move straightly along the linear guide way by human users. The cylinder rod is rigidly connected with the handle, and the cylinder barrel rigidly connects with the base plate. The moving range (Sl) of the handle is set to 300 mm.

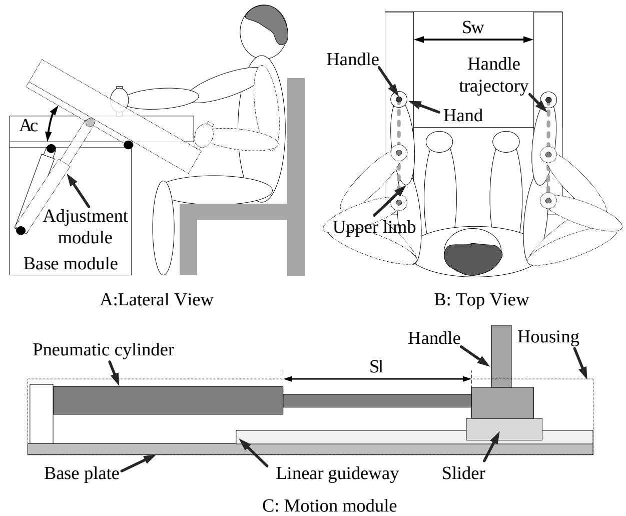



Figure 2. Schematic description of the adjustment and motion mechanism. (Ac: Angle of inclination, Sw: Width between two sides of motion module, Sl: Moving range of handle)

### B. Pneumatic Design

Variable resistance of the bilateral robotic system can be adjusted based patients' disability levels. The motion module employs two pneumatic cylinders whose air flow change leads to variable resistance. This study uses different combinations of throttle valves for different air flows control.

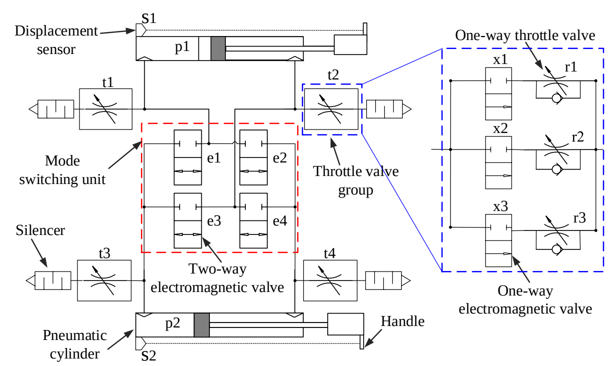


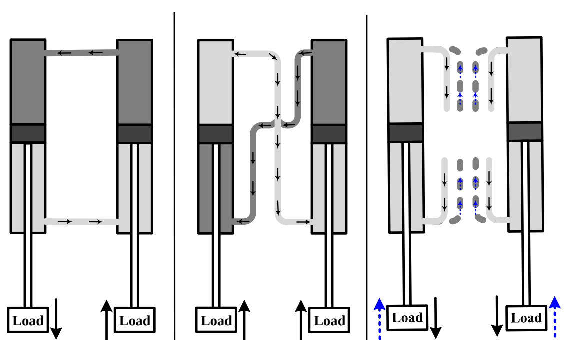

Figure 3. The pneumatic schematic of the bilateral robotic system. (The mode switching unit in a red square and the throttle valve groups in a blue square)

The pneumatic schematic of this bilateral robotic system is presented in Figure 3. It contains three main parts: two pneumatic cylinders (p1-p2: CHSCS MAL20-300), a mode switching unit (in a red square) composed of four two-way electromagnetic valves (e1-e4: CKD 3PA110), four throttle valve groups (in a blue square), each consisting of three one-way throttle valves (r1-r3: Airtac ASC100-06), and three one-way electromagnetic valves (x1-x3: Airtac 2V025-06).

Due to the mode switching unit in Figure 3, the device can be operated with three different movement modes: bilateral asynchronous movement, bilateral synchronous movement and bilateral independence movement. The air circulation of each mode is shown in Figure 4. If the electromagnetic valves in the mode switching unit are all closed, motion resistance of each pneumatic cylinder is independently controlled by the corresponding throttle valve group, as shown in Figure 4 (c). The patient could put his/her arms on two handles and actively push or pull them to accomplish bilateral training under different resistance levels. Since both sides of the motion module are independent to each other, the coordination of the bilateral upper limb is completely controlled by patient himself/herself.

Different with the mode (c) for independent bilateral movement, the bilateral asynchronous movement mode (a) and bilateral synchronous movement mode (b) lead to an interaction effect on the two handles.

Under the bilateral asynchronous movement mode (a), the electromagnetic valve e1 and e4 in the mode switching unit are open, the four throttle valve groups are closed, two rodless chambers of the cylinder are connected with each other, and the two rod chambers do in the same way. When one human arm pushes the handle, inner air of the cylinder is forced to flow to the connected chamber, causing the other handle to pull. The bilateral synchronous movement mode (b) is nearly same as the mode (a), except that the handles move in the same direction. The implementation of this mode requires to open the electromagnetic valve e2 and e3.




a. Asynchronous movement b. Synchronous movement c. Independence movement

Figure 4. Air circulation of three working modes.

Further about the throttle valve groups, they are used to adjust and control the resistance of the linear movement of the hand. It should be noted that these throttle valve groups are just needed for the mode (c). In this study, each throttle valve group consists of three one-way throttle valves (r1-r3) for adjusting the air flow. To achieve different flow configurations, we set the position of valve spool according to its flow characteristic curve, valve x1 to 15L/min, x2 to 27L/min, and x3 to 80L/min. Different combinations of these three throttle valves can result in eight different levels of air flow values, as in Table 1.

TABLE 1. COMBINATION RESULT OF THROTTLE VALVE

| **B** | **A** | **Combination** | **Valve flow*** | | |
|---|---|---|---|---|---|
| | | | 15 | 27 | 80 |
| 5 | VIII | 0 | × | × | × |
| 4 | VII | 15 | √ | × | × |
| 3 | VI | 27 | × | √ | × |
| - | V | 42 | √ | √ | × |
| 2 | IV | 80 | × | × | √ |
| - | III | 95 | √ | × | √ |
| - | II | 107 | × | √ | √ |
| 1 | I | 122 | √ | √ | √ |

*the data is given under 0.6Mpa and unit is L/min; √ represents selected; ×means not selected.

Specifically, when all valves shut down, the flow is 0 L/min, when all open, the maximum flow is about 208 L/min. Considering that throttle effect is not obvious with bigger flow, only level I, IV, VI, VII, VIII in column A are used for resistance adjustment and they are renumbered as level 1-5 in column B.

## C. Electrical System

The electrical component of this robotic system consists of two displacement sensors (s1-s2: Panasonic HG-C1400), 16 electromagnetic valves, an electric telescopic rod and an embedded controller (NI myRIO-1900). The electromagnetic valves and electric telescopic rod are controlled by digital input/output (DI/O) of myRIO. The displacement sensors' signal are read by the analog input (AI), which provide the handles' position feedback to the system. The speed and acceleration feedback is calculated from the position feedback. Controlling the electric telescopic rod stretching out and drawing back, the angle of inclination of the motion module with respect to the base varies from 0◦ to 40◦. Inclination feedback is provided by the built-in gravity accelerometer of myRIO. The Z axis of the gravity accelerometer is perpendicular to the plane of the motion module, its X axis is parallel to the handle path. Considering the moving speed is slow and stable, the angle of inclination of the motion module is calculated in (1).

$$\alpha = \arctan\left(\frac{G_z}{G_x}\right) \tag{1}$$

Where α is the angle of inclination, $G_z$ is the reading on the Z axis, $G_x$ is the reading on the X axis.

## D. Interactive Gaming

A game is designed to guide human users for bilateral upper limb training. For early-stage rehabilitation, a good game should be easy to play, have direct mapping relationship between the arm motion and the game target.

The length of bar 1 and bar 2 represents the displacement of the left and right handle or human hand, respectively. The position of bar 3 is decided by bar 1 and bar 2. When a human user actively drive both handles, bar 3 will move around on the screen. For a therapy task, the participant is required to drive bar 3 to track bar 4. The bar 4 (a static target) appears on the screen randomly. When bar 3 gets into the target bar 4, the participant is required to keep the target on for a few seconds. While the time runs out, the participant is guided to complete the next round. The way how the bar 3 is driven, involving the driving speed, distance, and the targeting accuracy, can be recorded for evaluation of the training efficacy. Figure 5 shows an interactive game developed in labVIEW for robot-assisted bilateral upper limb training.

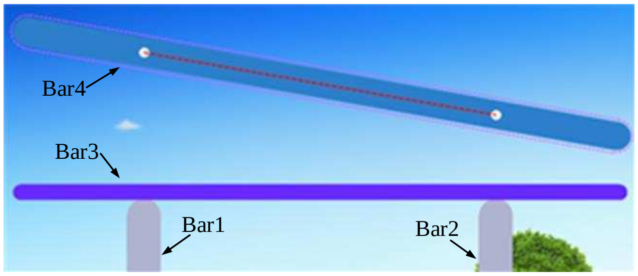



Figure 5. An interactive game to direct bilateral upper limb training.

## III. Experiemntal Results

### A. Resistance tests with constant speed

To evaluate different levels of resistance, this study used a linear module to simulate a human hand with a constant moving speed. The slider of the linear module is fixed to one end of a force sensor. Its the other end rigidly connects with the handle. The setup of the experiment is shown in Figure 6.

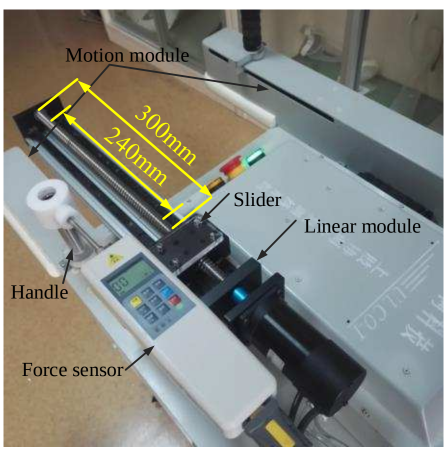



Figure 6. Setup of the resistance test with a constant moving speed.

This experiment aimed to test the resistance characteristic under each level. The resistance level of the motion module can be affected by both the throttle valve groups and the driving speed. To evaluate the role of different valve groups, the experiments were conducted at a constant speed of 200 mm/s. Specifically, the slider of the linear module runs forward (push) at 200 mm/s, then hold for five seconds, then the slider runs backward (pull) at the same speed, and finally stops. While the whole range of the motion module is 300 mm, this study selected the middle 240 mm for resistance tests to eliminate random errors, as in Figure 6.

By operating the corresponding electromagnetic valves of each configuration, as in Table 1, five levels of handle resistance were tested in sequence with results presented in Figure 7.

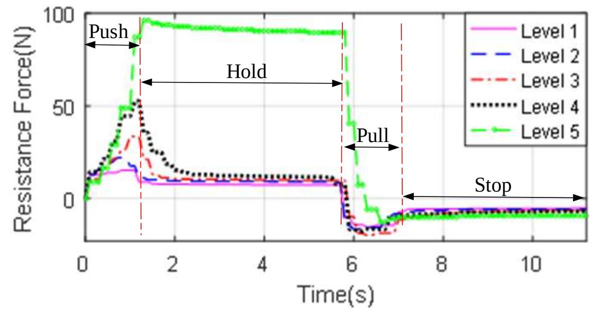



Figure 7. Characteristic of each resistance level at 200mm/s.

In Level 5, all electromagnetic valves are shutdown, which means the air in the cylinder chamber is sealed. This is its main difference with other four levels. With the handle pushing, the volume of the sealed air reduces and the pressure increases. When the handle is pushed to the end, the generated pressure reaches the peak that means the maximum resistance to human users. As in Figure 7, the maximum resistance is about 94.9N. During the five seconds holding stage, the generated resistance keeps at a relatively stable level. The force variation during the pull stage is nearly opposite with that of the push period.

The force variation of the other four levels behave to be similar, except their different force peaks. The maximum resistance force decreases as the level decreases (Level 4-52.5N, Level 3-33.6N, Level 2-22N, and Level 1-15.2N). In the pushing period, resistance increases along with the moving of the handle, when the handle reaches the end point, the resistance begins to decrease quickly since the air sealed in the cylinder chamber leaks quickly through throttle valves. Frictional resistance results in negative values of the force sensor when the handle is back to its origin (Stop stage).

### B. Resistance tests with variable speeds

To further investigate the influence of different driving speeds on resistance of the motion module, experiments were conducted with the same throttle valve groups (here Level 4 was selected).

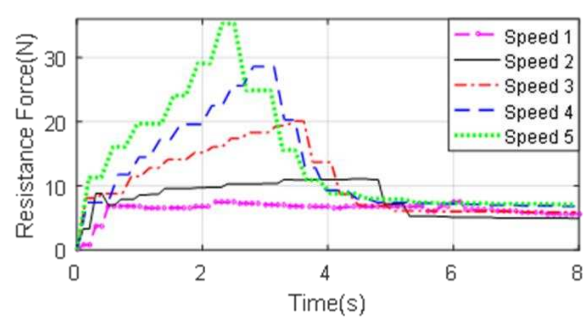



Figure 8. Resistance force characteristic of level 4 at different speeds. (Speed 1:13.3mm/s, Speed 2:33.3mm/s, Speed 3:66.7mm/s, Speed 4: 100mm/s, Speed 5:133mm/s)

The setup shown in Figure 6 was adopted for this test, where five different driving speeds were given. The corresponding results are presented in Figure 8. It is worth mentioning that from 0 second to the peak moment belongs to the push stage, and the remaining time is for holding until the $8^{th}$ second.

Obviously it can be found in Figure 8 that with the driving speed increasing from Speed 1 to Speed 5, the resistance force reaches a higher peak value with less time. This feature can be considered as an adaptive resistance strategy that gives larger resistance for quicker moving speed.

### C. Qualitative feedback on variable resistance

This study implemented various resistance control on the robotic system through different combinations of three throttle valves. However, if this can generate acceptable and obviously different resistance levels by human users is not clear. To qualitatively evaluate the differences of these five resistance levels, 11 healthy subjects volunteered to participate in this test. Each of them was required to conduct the push-hold-pull-stop movement under five resistance levels. For the test, these five levels of resistance are randomly arranged. Immediately after the test, each participant was required to reorder the resistance levels based on their feelings. The test design and participants' feedbacks are summarized in Table 2.

TABLE 2. QUALITATIVE RESISTANCE TEST DESIGN AND FEEDBACKS FROM ALL PARTICIPANTS

| No. | Sex | Age | Random order | | | | | Feedback | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1* | M | 20 | 2 | 4 | 5 | 3 | 1 | 3 | 4 | 5 | 2 | 1 |
| 2 | F | 20 | 5 | 3 | 2 | 1 | 4 | 5 | 3 | 2 | 1 | 4 |
| 3 | F | 21 | 5 | 2 | 1 | 3 | 4 | 5 | 2 | 1 | 3 | 4 |
| 4 | M | 21 | 2 | 3 | 4 | 1 | 5 | 2 | 3 | 4 | 1 | 5 |
| 5 | M | 23 | 3 | 4 | 5 | 2 | 1 | 3 | 4 | 5 | 2 | 1 |
| 6 | F | 21 | 4 | 2 | 3 | 1 | 5 | 4 | 2 | 3 | 1 | 5 |
| 7 | M | 31 | 2 | 3 | 1 | 5 | 4 | 2 | 3 | 1 | 5 | 4 |
| 8 | M | 20 | 1 | 4 | 3 | 2 | 5 | 1 | 4 | 3 | 2 | 5 |
| 9 | F | 24 | 1 | 4 | 5 | 3 | 2 | 1 | 4 | 5 | 3 | 2 |
| 10* | F | 21 | 2 | 1 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| 11 | M | 22 | 1 | 5 | 3 | 4 | 2 | 1 | 5 | 3 | 4 | 2 |

* represents the participants with mistakes in ordering the resistance level, and all others gave the right sequence.

As shown in Table 2, 1 out of 11 (9.1%) volunteers mixed up level 2 and 3, 1 out of 11 (9.1%) volunteers mixed up level 1 and 2, the others (81.8%) managed to identify the correct resistance level as the predefined random orders.

### D. Qualitative feedback on the robotic system for bilateral training

The 11 participants also played the game with this robotic system under three working modes, of which the bilateral independent mode also has five levels of resistance. After the test, each of them was required to give feedback based on a questionnaire. It consists of two ranking based questions and ten selective questions. Two ranking based questions contain "how interesting do you think is the performance of the game, are you satisfactory with the training effect". Eight selective questions contain "Which level do you think a stoke patient could bear, is width between the handles suitable for you, do you feel uncomfortable during the training, do you think the bilateral asynchronous mode and bilateral synchronous mode are useful in rehabilitation training". Any other comments involving this virtual-reality tracking game are also welcome to give if available.

The purpose of this test is to evaluate people's feelings with this robotic system for bilateral upper limb training. Before any test, each participant was requested to understand the game with a demo about how it works.

Results show that two participants have previous experience in using rehabilitation equipment. The others have little knowledge of rehabilitation devices. Nine participants give a six or higher score for the game enjoyment and training effect. Ten of them considered resistance levels 1-4 to be suitable for human users' bilateral training. The two participants with previous experiences of using rehabilitation devices also suggested that the bilateral asynchronous mode and the synchronous mode will bring extra difficulties and challenges in tracking the predefined targets within the game. Both are happy with this two new modes, but definitely suggested to further investigate how such modes can be brought into practice.

## IV. CONCLUSION

This paper presents the development of a pneumatic robotic system for bilateral upper limb training with variable resistance. It makes use of the atmosphere air to produce resistance, which does not require external power source and thus leads to more enhanced training safety.

Quantitative experiments were conducted in a lab environment to evaluate the variable resistance performance of this robotic system. Qualitative feedbacks were also obtained from each participant. Results show that the robotic system is able to deliver appropriate bilateral training with different levels of resistance. Most participants gave a positive feedback in using this device for bilateral upper limb training.

However, the proposed robot-assisted bilateral training techniques suffer from a limitation of unstable resistance even with constant driving speed. Future work will focus on developing new control techniques to achieve constant resistance even with different driving speeds. The modelling of the synchronous and asynchronous modes will be also explored for more accurate control, enabling its clinical applications.

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