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A design of fine motion assist equipment for disabled hand in robotic rehabilitation system[☆]

Satoshi Ito[a,*], Haruhisa Kawasaki[a], Yasuhiko Ishigure[b],
Masatoshi Natsume[c], Tetsuya Mouri[a], Yutaka Nishimoto[d]

[a]*Faculty of Engineering, Gifu University, Yanagido 1-1, Gifu 501-1193, Japan*
[b]*Marutomi Seiko Co., Ltd, Ikuda 3147-7, Kurachi, Seki 501-3936, Japan*
[c]*Facility Management Division, Gifu University, Yanagido 1-1, Gifu 501-1193, Japan*
[d]*School of Medicine, Gifu University, Yanagido 1-1, Gifu 501-1193, Japan*

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Abstract

This paper reports a newly designed system intended to aid in hand rehabilitation. The motion assistance equipment consists of three parts: mechanisms for the fingers and thumb, a base of these mechanisms, and a motion assistance mechanism for the wrist. The structure of each mechanism is designed to achieve independent, fine motion assistance, especially, for the individual fingers. First, the features of each mechanism in the equipment are explained. Next, the control systems are introduced, which are constructed to realize a self-motion control strategy (i.e., the motion is controlled by its user). Using this control system, the transient response and steady state characteristics of the motion assistance mechanisms for the thumb are evaluated. Consequently, the possibility of practical application is found in regard to some improved points.

Keywords: Rehabilitation; Robot system; Hand; Mechanism; Motion assistance

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[*] Corresponding author. Fax: +81 58 293 2540.

E-mail addresses: satoshi@gifu-u.ac.jp (S. Ito), h_kawasa@gifu-u.ac.jp (H. Kawasaki), ishigure@marutomi.co.jp (Y. Ishigure), natsu@gifu-u.ac.jp (M. Natsume), mouri@gifu-u.ac.jp (T. Mouri), yutaka@gifu-u.ac.jp (Y. Nishimoto).

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1. Introduction

The number of elderly persons in Japan is increasing [1], and these individuals have a strong chance of being involving in accidents due to their decreased ability to engage in physical exercise. In addition, it is highly possible that in elder persons disorders such as strokes will affect their limb movement. Rehabilitation is required for the recovery of such functions which have been limited by injuries or disorders. Thus, the increase of disabled persons in Japan's aging society demands the development of rehabilitation systems. Especially, an enjoyable rehabilitation activity that patients can perform effectively by themselves is important for future rehabilitation systems, considering the limited number of caregivers owing to Japan's reduced birthrate or to inadequate medical facilities in a provincial area [1,2].

Recently, rehabilitation systems introducing robotic technology or virtual reality have been proposed in order to achieve effective training or telerehabilitation [3–5]. Among these rehabilitation systems, those for the upper limbs are extensively studied, where the target is the arm or hand. Rehabilitation devices for arm movement have been widely reported [6–12], with these studies including clinical tests [12–14]. On the other hand, a device for hand rehabilitation is somewhat difficult to develop because the hand possesses many degrees of freedom (DoFs) of motion and its moving parts are relatively small. Similar devices, including those involving force feedback groves used in virtual reality or teleoperation technologies have been previously developed [15–17]. These devices are usually structured using an exoskeleton, and do not provide actuation in the direction of abduction/adduction. When clenching and unclenching ones' hands, abductions/adductions in finger motions occur naturally. Thus, a mechanism to assist these motions is needed in hand rehabilitation devices. In addition, such a device should bilaterally assist in the flexion/extension of the fingers. However, many of the hand devices in current development can provide only unilateral extension, though bilateral assistance is achieved using a spring mechanism in [18] or Bowden cables in [19]. Opposing motion for the thumb is indispensable for grasping objects. However, the structure of the carpometacarpal (CM) joint in the thumb is specific and thus current rehabilitation hand devices cannot perform sufficient motion assistance for opposing motion.

In our project, we designed a hand rehabilitation equipment that can assist the following motions, all of which the existing devices are not capable of:

- bilateral motions in the flexion/extension of each finger,
- abduction/adduction of each finger, and
- opposing motion of the thumb.

A prototype of the hand rehabilitation equipment has been developed, which is capable of 18 DoFs of motion, 3 DoFs for assisting each finger, 4 DoFs for the thumb, and 2 DoFs for the wrist. Focusing on the assistance of the motion of the opposable thumb, this paper presents the structure of the hand rehabilitation equipment and the control system for operating it. For upper limb rehabilitation, a method in which laterally symmetrical motions are supported in a training program using robotics technologies has been proposed [20] and its effects reported [21], but it has not yet been practically applied to hand rehabilitation. With the aim of achieving strong training benefits, in the present paper we describe the design of a self-motion control strategy for hand rehabilitation through the use of a master–slave control: the normal hand, acting as the master side, produces the training motion for the affected hand, i.e., the slave side.

2. Mechanical design

2.1. Overview of motion assistance equipment

The motion assistance equipment that we designed consists of three parts: mechanisms for the fingers and thumb, a mobile base of mechanism for them, and a mechanism for the wrist, as shown in Fig. 1. The mechanisms are separately developed for four fingers and the thumb as illustrated in Fig. 2. The noticeable difference is found in the DoF of motion, which will be addressed in the next subsection. The mechanisms are attached to the base by screws, which allows the position of the mechanisms to be adjusted to fit various hand sizes. The mechanism for the wrist realizes two DoFs of motion assistance: procurvation/dorsiflexion and pronation/supination.

2.2. Design of mechanisms for fingers

Roughly speaking, four DoFs are found in the motion of human fingers: extension/flexion for the metacarpophalangeal (MP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints, and abduction/adduction of the MP joint. Among them, the motions of the PIP and DIP joint occur simultaneously, i.e., are not independent. Thus, three independent motions without the DIP joint are selected as the assistance motions in this rehabilitation system.

The developed motion assistance mechanisms for the fingers are shown in Fig. 2(a). The first and second motors are fixed at the base and assist the two DoFs of motion at the MP joint: the first motor assists the abduction/adduction of the MP joint while the second one assists extension/flexion. Their rotation axes are designed so as to be orthogonal to each other, which makes the calculation of the kinematics of the link mechanism simple. The

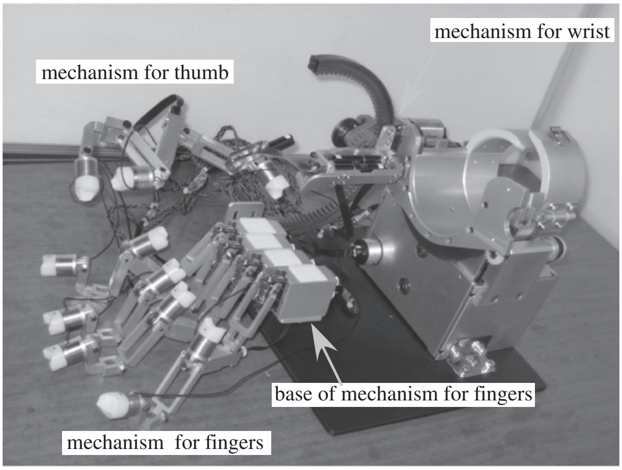

Fig. 1. Photo of the motion assistance equipment.

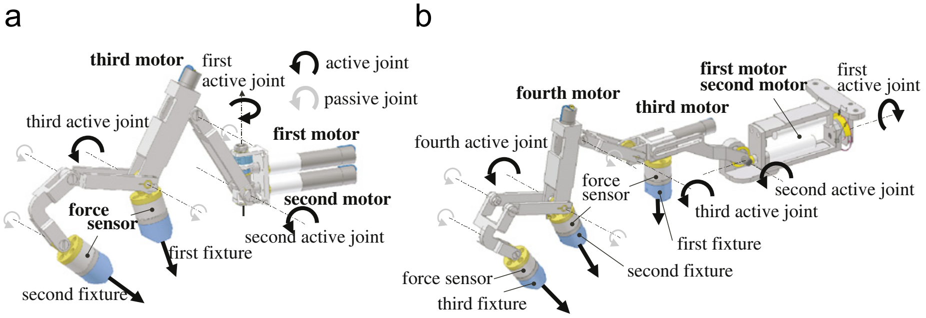

Fig. 2. Structure of mechanisms: (a) mechanism for fingers and (b) mechanism for thumb.

fixing points of the finger are three-link distal from the base, implying that two passive joints exist between the active joint and the first fixture of the finger. The distance between the active joint and the second passive joint varies thanks to the first passive joint, and thus the fixture can maintain the normal direction of the finger. Consequently, the link mechanism and finger form a closed link structure that is expected to transfer the driving force of the motor for the disabled joint. The dorsal part of the finger between the MP and PIP joints is attached to the first fixture, while a part of the back of the hand is attached to the base. Velcro straps are used to attach the hand to each part of the equipment, since they are easy to put on and remove. The distal part of this mechanism possesses the same structure as described above, which assists the extension/flexion of the PIP joint. The motor for the assisting motion is built into the second link from the base in order to secure a sufficient range of motion (ROM) for each joint without mechanical interference. The dorsal part of the finger between the MP and PIP joints is attached to the second fixture.

Two closed link structures are formed when the finger loads the equipment. In the first test model of this equipment, two closed link structures strike each other [22], which limits the motion of the link. The equipment described in this paper is designed to solve this problem.

The kinematical relation in the closed link structure enables us to calculate the MP/PIP joint angles based on the active joint angles detected from the built-in rotary encoder, and vice versa: the MP and PIP joint angles are denoted by q_1 and q_2, respectively, while the active joint angles are θ_1 and θ_2, as shown in Fig. 3. For example, when the MP joint angle flexes in q_1, the angle that the mechanism must take is obtained by the following steps: first, the link joint position (x_1, y_1) and (x_2, y_2) are given as

$$(x_1,y_1)=(0,L_1),\quad (x_2,y_2)=(f_1+f_2\cos q_1+L_4\sin q_1,-f_2\sin q_2+L_4\cos q_1) \tag{1}$$

where L_i $(i=1,\dots,7)$ denotes the length of the link of the mechanisms and f_i $(i=1,2)$ is the length of a part of the human finger. Next, the angles ϕ_1 and ϕ_2 can be calculated as follows:

$$\phi_1=\cos^{-1}(\ell_1^2+L_2^2-L_3^2)/2\ell_1L_2,\quad \phi_2=\cos^{-1}(\ell_1^2+L_1^2-\ell_2^2)/2\ell_1L_1 \tag{2}$$

where

$$\ell_1=\sqrt{(x_1-x_2)^2+(y_1-y_2)^2},\quad \ell_2=\sqrt{x_2^2+y_2^2} \tag{3}$$

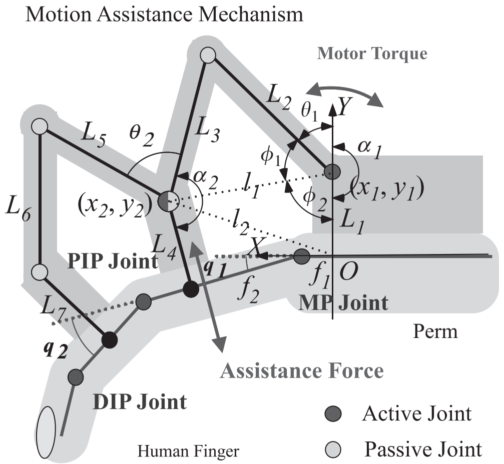

Fig. 3. Closed link structure composed of the mechanism and finger.

Finally, the objective angles θ_1 is given by

$$\theta_1 = 2\pi - \phi_1 - \phi_2 - \alpha_1 \tag{4}$$

This is a kind of inverse kinematics. The forward kinematics can be solved in the same way. Here, the length of each link, i.e., from L_1 to L_7 is selected from the statistical data describing the finger sizes of Japanese adults, thus allowing the equipment to fit the hands of the broadest majority of the elderly population.

To detect the force that is exerted between the equipment and the finger, force sensors are embedded in the fixture. The required motor torque is determined based on the experimental measurements, where the therapists were asked to apply the force to the torque gauge as if it were the finger of a disabled person under rehabilitation. The motors produce torque within a sufficiently safe range so that therapists do not consider that the equipment will injure disabled persons with delicate physiques [23].

2.3. *Design of mechanism for the thumb*

The motion of the thumb is different from those of the other fingers such as, for example, the MP joint that performs only extension/flexion. Instead, abduction/adduction are performed at the CM joint that also has DoF for extension/flexion. Owing to this motion, the thumb is able to touch each of the other fingertips. Taking these properties into consideration, the mechanism is designed differently for the thumb, as shown in Fig. 2(b). The mechanism assists the extension/flexion of the MP and IP joints. For the CM joint, however, the first and second motors fixed at the base assist two DoFs of motion. The first motor assist the abduction/adduction by which the trajectory of the line connecting the rotation center and the tip of mechanism from the cone as illustrated in Fig. 4, while the second motor assists the extension/flexion that changes the apex angle of the conic motion.

As in the mechanism used for the fingers, force sensors are embedded in the fixture for the thumb. The back of the hand, the dorsal part of the thumb between the CP and MP

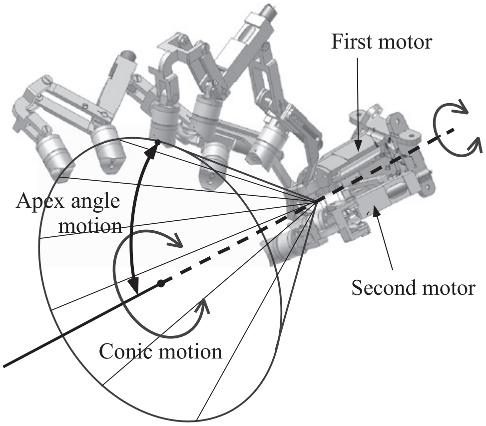

Fig. 4. Conic motion-assisting CM joint.

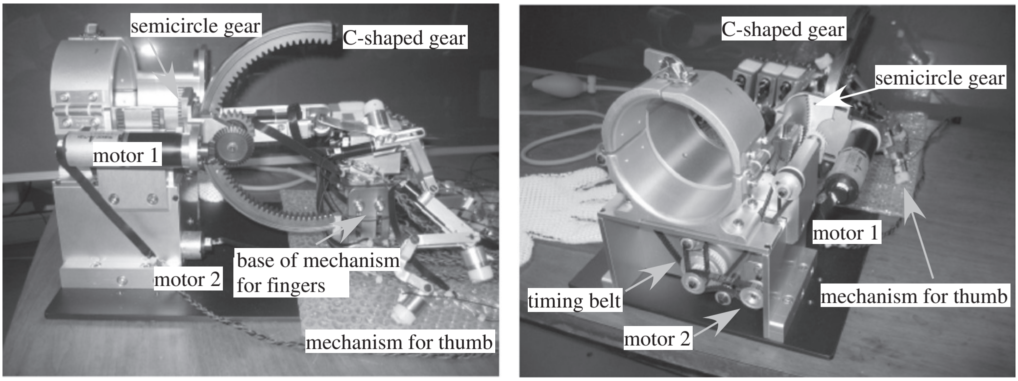

Fig. 5. Motion assistance mechanism for the wrist.

joints, and the one between the MP and interphalangeal IP joints are attached to three fixtures. As a result, this mechanism and the thumb form three closed link structure.

2.4. Design for mechanism for the wrist

The human wrist performs three different motions: procurvation/dorsiflexion, abduction/adduction, and pronation/supination. Among them, training weight is applied in procurvation/dorsiflexion as well as in pronation/supination in hand rehabilitation. The mechanism for the wrist is designed in light of this, whose photos are shown in Fig. 5.

The arm is fixed to an immobile part of the equipment, while the back of the hand is fixed to the base that can move with the mechanisms for the fingers and thumb. The base is fixed to a C-shaped gear, and the C-shaped gear rotates around its center that is located on the rotation axis of the procurvation/dorsiflexion of the wrist. Thus the rotation of C-shaped gear, driven by motor 1, moves the base up and down so as to assists in procurvation/dorsiflexion. The range of this motion covers ±90°. For assisting in pronation/supination, the base, the C-shaped gear as well as the mechanisms for the fingers and thumb also rotates along the rotation of the semicircle gear. The rotation axis is designed to coincide with that of procurvation/dorsiflexion. This rotation is driven by motor 2 via timing belts.

3. Control system

Most disabled persons who need hand rehabilitation are disabled only on one side of the body. For example, cerebral stroke results in hemiplegia. Thus, a self-motion control strategy is adopted in which the affected hand is controlled by commands from the unaffected hand so as to produce bilaterally symmetrical motions. This strategy is selected from the following reasons:

- Because the hands are symmetrical in both sides, the assistance motions do not exceed the ROM of each joint.
- Users can stop exercises by themselves if they feel pains.
- This control strategy is expected to be effective, because users can exercise with imaging training movement that the affected hand should perform through unaffected movement.

With regard to the motion of the unaffected side, the angles of the finger joints are detected using a data glove. Information describing the unaffected hand's posture is also displayed to the disabled user using computer graphics, which enable the user to recognize the hand's state of motion visually. According to inverse kinematics, the reference angles for active joints of each motion assistance mechanisms are computed so that the affected hand takes the same posture as the unaffected one. These reference angles are transmitted to the controller of the motion assistance equipment through TCP/IP communication. The personal computer operated by Windows OS is used to perform the above tasks.

At the controller of the motion assistance equipment, the position of the joint is controlled to the reference angles that are received via TCP/IP communication. The current joint angles of each motor are detected by the rotary encoder installed to the motors. In addition, force information can be measured from the force sensors attached to the fixtures, though they have not yet been utilized in this report. Using this information, the required torque is calculated in the position controller and sent to the motor drivers as the driving PWM signal. Finally, the motors actuate the active joints followed by this signal to assist the affected hand motions. A real-time operation system (ART-LINUX) is adopted to ensure periodical sensor sampling and motion generation

4. Motion test experiments

A key feature of this motion assistance equipment concerns the design and manufacture of the motion assistance mechanism for the thumb. In this equipment, the motion assisting the CM joint is essential, because the opposable motion of the thumb cannot be achieved without it. This is a reason why the assistance motion for the CM joint was the main focus of our investigation described below.

4.1. Step response experiments

To examine the system's dynamic characteristics, the tracking property of the step input was observed. The reference signal was made by suddenly switching input values every 5 s from −0.2 to −0.7 rad. This range was chosen to be large enough for the thumb to achieve opposable motion. Two cases were measured: (a) free motion and (b) constrained motion. In case (b), a sponge-packed rubber glove instead of a human hand was used to test the equipment, while no object was used in case (a). The duration of the experiment was 25 s and three sets were executed. The proportional control was applied with the gain set at 10. The control period was 1 ms.

The time course of the active joint angles assisting the CM joint as well as its reference is depicted in Fig. 6. In the graphs, the four sets of measured data are overlaid with their average. Fig. 6(a) shows the results for case (a). The CM joint almost converges to its reference values. The deviation is very small among these data, implying a high degree of reproducibility of the CM joint motion. The rise time derived from the averaged data is 0.32 s for the antigravity direction from −0.2 to − 0.7 rad, while it is 0.28 s for the reverse direction. The difference of the rise time between these directions will arise from control without gravity compensation.

Fig. 6(b) shows a result for case (b). The graph shows the same physical values as seen in Fig. 6(a). This case also shows a high degree of reproducibility. The joint angles can follow the reference signal closely, but this acceptable result is partially owing to the Velcro straps that produce looseness at the attachment between the fingers and the mechanisms. The rise time derived from the averaged data is 0.31 s for the direction from −0.2 to −0.7 rad, while it is 0.29 s for the reverse direction. The difference in rise time between cases (a) and (b) is due to the elasticity of the rubber glove. In terms of control, tracking the fast-varying reference signal is preferable. However, a too-quick response sometimes causes dangerous motions, for example, due to careless motions of the unaffected hand. Future clinical tests are intended to assess the response speed.

4.2. Experiments regarding the self-motion control

To assess the possibility of the system's practical application, experiments evaluating the self-motion control were performed. Their main purpose was to examine whether the

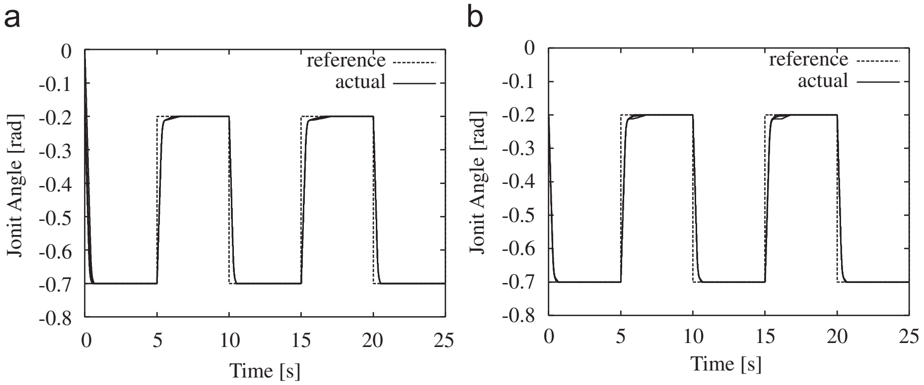

Fig. 6. Step response: (a) free motion and (b) constrained motion.

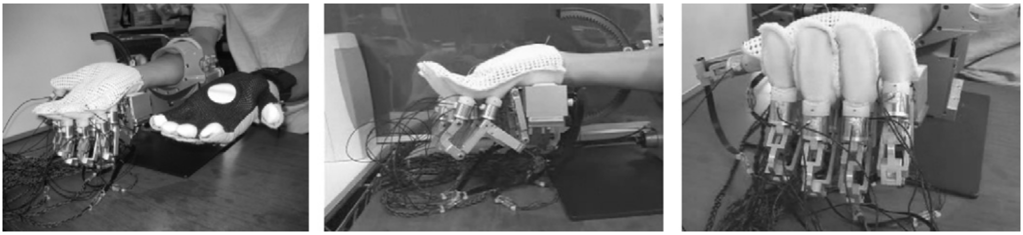

Fig. 7. Snapshot of the self-motion control experiment.

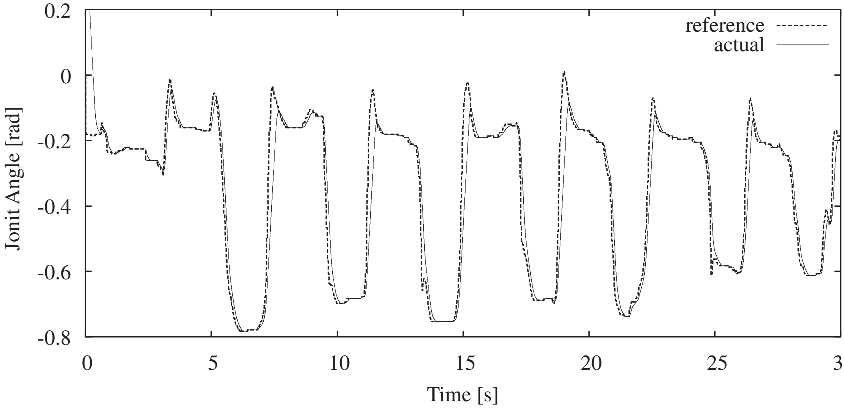

Fig. 8. Result of the self-motion control experiment.

active joint smoothly follows the reference signal generated from the unaffected hand motion. In the experiment, a normal unimpaired subject was asked to repeatedly open/close his left thumb and forefinger wearing the data glove, and to have the right hand fixed to the motion assistance equipment and to allow it to relax so that it could conform to the assisting motion imposed on it. Data regarding the left hand motion was detected by the data glove every 10 ms, and the reference angles were sent through the system according to the same rate. Photographs of the experiments are shown in Fig. 7.

The time courses of the angle of the active joint for assisting the CM joint as well as its reference are shown in Fig. 8. The measured data indicates that the motion of the active joint conforms closely to the desired one calculated based on the opposite hand with data glove. However, as mentioned regarding the previous experiment, the looseness of the Velcro straps fixation cannot be ignored. An improved method for fixing the equipment to the hand is required.

5. Concluding remarks

This paper reports the design of fine-motion assistance equipment for hand rehabilitation and describes the results of its experimental evaluation. Although some points should be improved, the possibility for the system's practical application is demonstrated through the experiments. Now, the experimental test of the wrist motion is executed. Based on the experimental results regarding wrist motion, further improvements in the system can be expected.

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