RESEARCH ARTICLE OPEN ACCESS

An Exoskeleton-like Robot Mechanism for Neck Rehabilitation Training

Wang Yilin[1], Chen Zhe[1], Li Jiabao[1], Liu Qihua[1], Zhang Yinwu[1], Qin Pengcheng[1], Hang Lubin[*1,2]
(1.School of Mechanical and Automotive Engineering, Shanghai University Of Engineering Science,Shanghai. 2.Shanghai Collaborative Innovation Center of Intelligent Manufacturing Robot Technology for Large Components, Shanghai.)

ABSTRACT
Targeting issues such as cervical discomfort and neurological diseases that result in complete inability to move the neck, it poses a threat to people's health and a better life. A medical device that can actively assist in neck rehabilitation training is crucial to overcome the limitations of conventional neck braces, which have a single supporting point and cannot achieve active rehabilitation. Taking into account the human body mechanism and the basic movement of the head, a 2-UPU spatial parallel-series hybrid mechanism with a single R series-parallel mechanism is proposed to effectively assist in neck rehabilitation training. The mechanism introduces a spherical gear to improve transmission accuracy and uses intermittent transmission of two sets of unipolar gears and spherical gears to achieve two degrees of freedom of nodding and shaking of the head without interference. A pair of ordinary gears are used to accomplish the rotation degree of freedom efficiently and achieve the three basic movements of the human head. The designed exoskeleton-like robot mechanism has multifunctionality and includes a cam mechanism for massaging the posterior neck acupoint, which further enhances the rehabilitation effect. A stepper motor control system is designed to achieve the assisted rehabilitation movement of the exoskeleton device.
***Keywords*- Exoskeleton-like robot mechanism** ; Neck Rehabilitation; Series-Parallel Hybrid Mechanism; Spherical Gear; Cam Mechanism; Traditional Chinese Medicine; .

Date of Submission: 02-05-2023 Date of acceptance: 12-05-2023

I. INTRODUCTION

In modern society, high-intensity work pressure and fast-paced lifestyle have made cervical spine discomfort a more common phenomenon; More seriously, there are many patients who are completely unable to move the neck due to neurological diseases. Therefore, there is an urgent need for a neck rehabilitation device that is comfortable to wear and can assist in rehabilitation.

In view of the fact that static cervical collars on the market cannot assist patients' rehabilitation training, scholars at home and abroad have successively carried out research on dynamic cervical collars (exoskeleton-like mechanisms). Chen Chaofeng of Harbin Institute of Technology designed a cervical spine rehabilitation exoskeleton based on a spherical parallel mechanism, and its three-dimensional model is shown in Fig. 1.1. Although the mechanism can assist the human body in neck rehabilitation to a certain extent, the device will block the person's vision.[1]

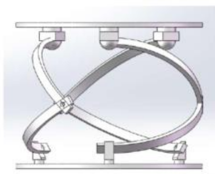


Fig.1.1 Cervical spine rehabilitation exoskeleton-like based on spherical parallel mechanism

Haohan Zhang et al. of Columbia University in the United States designed a three-degree-of-freedom dynamic neck brace, which is essentially a 3-RRS parallel mechanism, as shown in Fig.1.2. Although this kind of rehabilitation mechanism can assist the patient to move the head and achieve the purpose of cervical spine rehabilitation training, the device does not have the characteristics of decoupling, the control is difficult to achieve and the transmission accuracy is not high. In addition, the structure cannot massage the human neck and cannot promote neck healing by massaging the acupuncture points of the human body.[2]

Fig.1.2 Three-degree-of-freedom dynamic neck collar

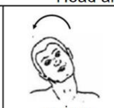
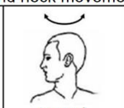
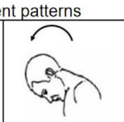
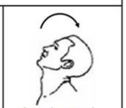
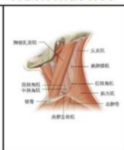
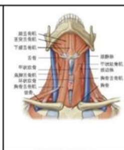
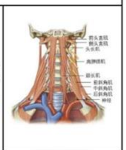
For the above problems, this paper proposes an exoskeleton-like series-parallel hybrid mechanism for neck rehabilitation training for rehabilitation of neck muscles. Among them, a multi-sport mode spherical tooth transmission mechanism is introduced; The structure has a cross spherical gear transmission mode, intermittent movement of basic spherical gear, and the two monopole gears in the device are arranged vertically, so that it can achieve intermittent motion and rotational movement with the spherical gear mechanism, and the two monopole gear inputs have decoupling characteristics to improve the transmission accuracy of the mechanism. Starting from wearing comfort, the control head movement linkage is symmetrically arranged on both sides of the moving platform, and the massage mechanism is located at the rear, and the overall design of the mechanism is reasonable, completely exposing the face without obstructing the line of sight. In addition, the application of traditional Chinese medicine treatment technology, the rear massage device mainly massages the back neck wind pool point, feng fu acupoint, Tianzhu acupoint, can further improve the rehabilitation training effect.

II. Analysis of Human Neck Movement and Exoskeleton Design

2.1 Physiological Mechanism of the Human Neck and Range of Motion

The primary biomechanical function of the neck is to transmit the load of the head to the thoracic vertebrae, providing a three-dimensional platform for head movement and protecting the spinal cord and other tissues within the vertebral canal. The overall movement of the head and neck relative to the trunk includes flexion, extension, lateral flexion, and rotation. Cervical range of motion refers to the range of motion of the cervical segment during physiological activity in the human body, which is mainly measured using radiographic equipment and a bi-planar stereo optical measurement system [3]. Based on the human biomechanics, skeletal dynamics, and ergonomics of the head and neck, design guidelines for the mechanism.

Table 2.1 Physiological mechanism of the human neck and range of motion

Head and neck movement patterns				
Diagram	 swing	 turned	 Bend forward	 backward
Activity angle	-55°~55°	-55°~55°	0°~35°	0°~40°
Neck muscles				
Diagram				
Main actions	turned Bend forward backward	turned Bend forward backward	Sidebend Bend forward	Open mouth and swallow

According to the head movement forms of the human body, the designed mechanism mainly consists of three movement forms: flexion and extension, lateral flexion, and rotation. Clinical medicine shows that cervical movement can be represented by range of motion. By measuring the range of cervical motion, the approximate range of lateral flexion, rotation, flexion, and extension can be obtained clinically, with a range of -55° to 55° for lateral bending, -55° to 55° for rotation, 0° to 35° for flexion, and 0° to 40° for extension. The physiological mechanism and range of motion are shown in Table 2.1. Based on the biomechanical analysis of the human neck, a 2-UPU mechanism is designed.

2.2 Design of Exoskeleton-like Robot Mechanism

By using intermittent and rotary motions between the spherical gear and the monopole gear, multi-mode and multi-degree-of-freedom motion characteristics are achieved. The human shoulder, monopole gear, and spherical gear are considered as fixed platforms, while the 2-UPU support chain and mobile platform are used to propose a 2-UPU spatial parallel mechanism, which cleverly realizes the nodding and tilting motion of the head and neck. A rotary mechanism is connected in series on the mobile platform to achieve twisting motion. Finally, a series-parallel hybrid mechanism is constructed, as shown in Figure 2.1, and the physical image of the exoskeleton device is shown in Fig 2.2.

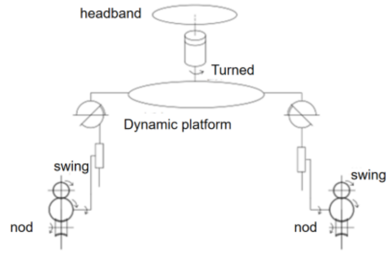


Fig.2.1 Schematic diagram of exoskeleton

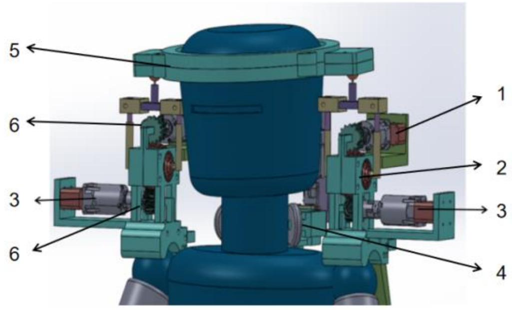


Fig.2.2 Physical image of exoskeleton device

As shown in Fig.2.2, the various parts of the exoskeleton device are labeled as follows: 1: Nodding motor; 2: Spherical gear; 3: Tilting motor; 4: Cam massage mechanism; 5: Headband; 6: Monopole gear.

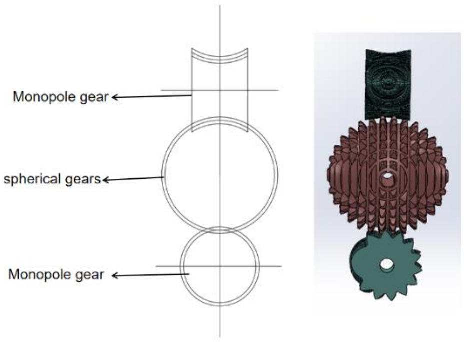


Fig.2.3 Schematic diagram of the meshing between the spherical gear and the monopole gear

The transmission mode of the spherical gear is shown in Fig.2.3, mainly relying on the two transmission characteristics of the monopole gear: gear meshing transmission and intermittent transmission. When either of the single gear drives the monopole gear, the other monopole gear will undergo intermittent motion without interference. By incorporating this mechanism into the exoskeleton device, the nodding and shaking motion of the head can be achieved based on this transmission property.

III. Motion Analysis of Exoskeleton-like Robot Mechanism

3.1 Nodding Motion

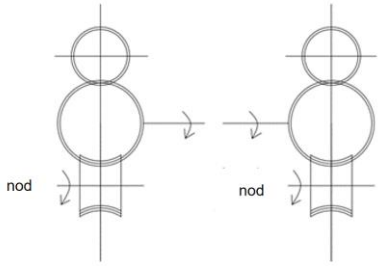


Fig.3.1 Position and driving method of monopole gears in nodding motion

When nodding motion, the stand-alone gear and spherical gear placement and drive mode are shown in Fig.3.1.When the mechanism realizes the motion platform's movement in the XOZ plane, P and R motion pairs are stiffened to simplify the analysis, and the 2-UPU mechanism is simplified to a parallelogram plane mechanism, as shown in the schematic diagram of Fig.3.2. Based on ergonomic principles, the spherical gear and monopole gear mesh to enable the R motion pair of the base to perform head nodding movements in the XOZ plane within the range of 0-45 degrees.

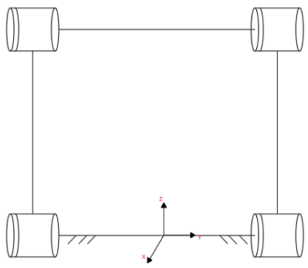


Fig.3.2 Schematic diagram of a parallelogram planar mechanism

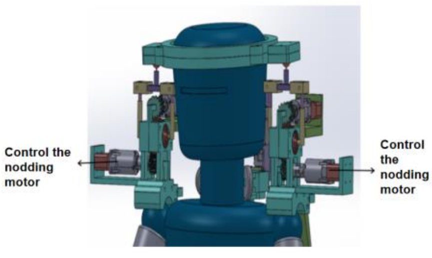


Fig.3.3 The original diagram of the mechanism controls the nodding situation

As shown in Fig.3.3, the nodding motion is achieved by the monopole gear connected to the two motors at the bottom. When the two motors rotate, they can drive the monopole gear to rotate. As the monopole gear engages with the spherical gear, the spherical gear will start to rotate, which in turn drives the connecting rods on both sides of the spherical gear and connected to the headband. Under the action of the connecting rods and the headband, the mechanism will move the head to complete the nodding motion. When the two monopole gears rotate in the same direction at the same speed, the mechanism will move the head forward and backward to complete the nodding motion. In addition, when the two monopole gears are driven separately by the motors, the mechanism can achieve left-forward, left-backward, right-forward, or right-backward motion. When the spherical gear is driven by the two motors at the bottom, the two monopole gears engaged with the spherical gear slide intermittently without interfering with the nodding motion.

3.2 Lateral Motion

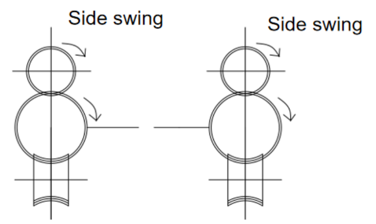


Fig.3.4 Positioning and driving method of unilateral gear with lateral swing motion

When swinging sideways, the placement and driving mode of the single gear and the spur gear are shown in Fig. 3.4. To simplify the analysis when the mechanism achieves the YOZ plane motion of the moving platform, the R motion pair is rigidified, and the 2-UPU mechanism is simplified to a 2-RPR planar mechanism as shown in the schematic diagram of the mechanism in Fig.3.5. Through the meshing of the spur gear and the single gear, the R motion pairs at both ends of the base can be rotated around the X-axis in the YOZ plane to achieve lateral movement of the head and neck.

The head and neck realize side swing motion, and the 2-UPU mechanism is simplified to 2-RPR planar mechanism. Based on the ergonomic principle and the motion characteristics of the spherical gear, it is known that the rotation range of the spherical gear in the plane is ±45°。

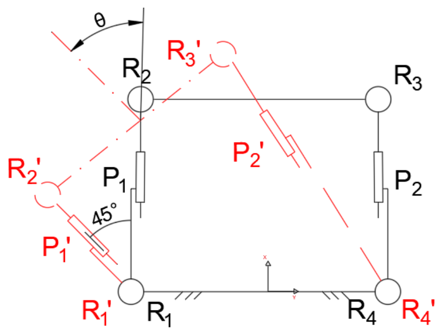


Fig.3.5 1Schematic diagram of 2-RPR planar mechanism and its oscillating motion

Set R1R2=R3R4=a, when driving R1 rotation pair and R4 rotation pair for 45°, set P1 moving pair h1 and P2 moving pair h2 (rod length variation h1, h2) as:

$$h_1 = (1 - \frac{\sqrt{2}}{2})\ a$$

$$h_2 = +\frac{1}{2}a$$

When rotating to the specified position, the changes of rod length R1 'R2' and R3 'R4' (L1, L2) at both ends are as follows:

$$L1 = \frac{\sqrt{2}}{2}a$$

$$L2 = \frac{3}{2}a$$

According to ergonomics, the neck is located at the middle point of the shoulder, and a rectangular coordinate system is established. The initial position coordinate is:

$$R_1 = (-\frac{1}{2}a, 0),\ R_2 = (-\frac{1}{2}a, a),$$
$$R_3 = (\frac{1}{2}a, a),\ R_4 = (\frac{1}{2}a, 0)$$

After rotation by 45°, the coordinate position is:

$$R_1' = (-\frac{1}{2}a, 0),\ R_2' = (-a, \frac{1}{2}a)$$

$$R_3' = (-0.6a,\ 1.1a),\ R_4' = (\frac{1}{2}a, 0)$$

So the $\overrightarrow{R_2'R_3'} = (0.4a, 0.6a)$, Its normal vector is theta $\vec{n_1} = (-1a, 0)$, $\vec{n_1} = (-0a, 0a)$

Then the Angle of the rod R_2 'R_3' relative to the normal vector $\vec{n_2} = (0, a)$ of the frame $\overrightarrow{R_1R_4} = (a, 0)$ is:

$$\cos\theta = \frac{\vec{n_1} \bullet \vec{n_2}}{|\vec{n_1}| \bullet |\vec{n_2}|} = 0.5547003924$$

$$\theta \approx 56.31^{\circ}$$

Therefore, when the driving spherical gear rotates ± 45 °, the head and neck rotate ± 56.31 °

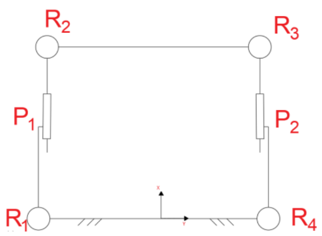


Fig.3.6 Schematic diagram of the 2-RPR planar mechanism

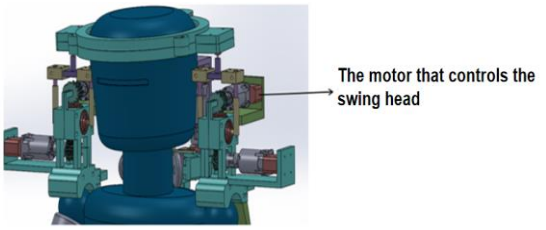


Fig.3.7 The original diagram of the mechanism controls the swing head situation

As shown in Fig.3.7, the lateral swing motion is achieved by a monopole gear connected to two motors from above. When the two motors above work, they can drive the monopole gear to rotate. At this time, the monopole gear rotates in the same direction and at the same speed, and due to its engagement with the globe gear, the globe gear undergoes meshing motion and is driven by the monopole gear. When the globe gear starts to move, it drives the connecting rods on both sides of the globe gear that are connected to the headgear, thereby causing the head to complete the left and right swing motion. During the lateral swing motion of the head, the two monopole gears that mesh with the globe gear below intermittently slide and do not interfere with the lateral swing motion.

3.3 Twisting Motion

Traction therapy is often the preferred or primary treatment for cervical spine disorders due to its proven efficacy for most patients. By applying cervical traction, the narrowed prevertebral space and intervertebral foramina can be enlarged, restoring the biomechanical balance of the cervical spine and reducing or eliminating clinical symptoms caused by nerve, blood vessel, and spinal cord compression. This therapy also helps to straighten the twisted vertebral artery and improve its blood supply, increasing effective blood flow [4].

Therefore, it is proposed to control the rotation of the head using a pair of gears and a traction rope, as shown in the schematic diagram of the headgear plane mechanism in Fig.8. The red circle represents the headgear worn on the head, which is pulled by a traction rope. The traction rope is connected to the gear. When the gear rotates, it can drive the head to achieve torsional motion.

As shown in Fig.3.8, there is a headband and headgear at the top of the mechanism. The headband and headgear are connected by a traction rope, which can effectively connect the human head to the entire mechanism and complete the twisting motion. As shown in Fig.3.9, the headgear consists of two gears, slots, sphericals, and a driving mechanism. The motor drives the small gear to rotate, and the small gear meshes with the large gear, driving the large gear to rotate. There is a traction rope on the large gear, which can drive the rotation of the head under the action of the traction rope. Small sphericals are embedded in the slots to reduce friction, allowing the gears to move smoothly and driving the rotation of the head.

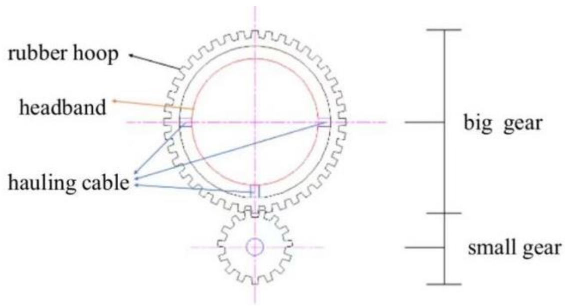


Fig.3.8 Diagram of the planar mechanism of the headband and transmission diagram

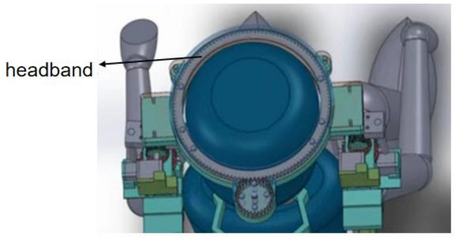


Fig.3.9 Headband part mechanism diagram

IV. Introduction to the Formation and Application of the Cam mechanism

4.1 Working Principle of the Cam mechanism

As shown in Fig.4.1, there are three types of motion generated by the interaction of gears: gear meshing, coupling, and intermittent motion [5]. When a single-lobe gear rotates around the y-axis, its teeth mesh with those of the cam mechanism, and the driving force is transmitted from the single-lobe gear to the cam mechanism. Coupling motion transmits driving force through the rolling rotation of the single-lobe gear, and intermittent motion caused by passive sliding on the tooth surface does not transmit driving force. When the pole of the cam mechanism and the single-lobe gear coincide, the rolling rotation of the single-lobe gear does not transmit any torque. If the single-lobe gear is fixed, the interaction of these three motions will constrain all movements except rotation around the structural axis, i.e., a single-lobe gear can constrain or drive two of the three rotational degrees of freedom in the cam mechanism.

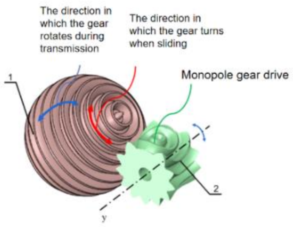


Fig.4.1 Schematic diagram of the movement of gear meshing and intermittent modes

4.2 The Generating Method of Spherical Gears

In this method, a coordinate system is established as shown in Fig.4.2. Two involute cylindrical gears are rotated 360 degrees around the x and y axes, respectively, forming a basic spherical gear as shown in Fig.4.3(a) and 14(b). If the basic spherical gear shown in Fig.4.4(a) is then processed as shown in Fig.4.3(b), as shown in Fig.4.4(a), the intersection of the two will form a new type of spherical gear as shown in Fig.4.4(b). The module of the cylindrical gears used is m=2 and the number of teeth is z=32.

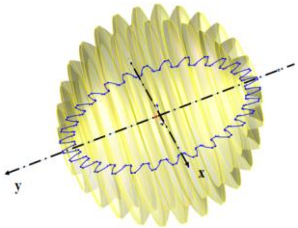


Fig.4.2 Establish a coordinate system based on basic spherical gears

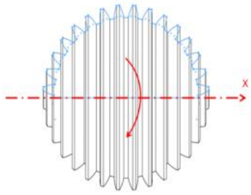


Fig.4.3(a) Schematic diagram of a basic spherical gear formed around the x-axis

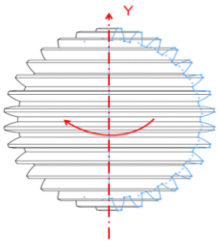


Fig.4.3(b) Schematic diagram of a basic spherical gear formed around the y-axis

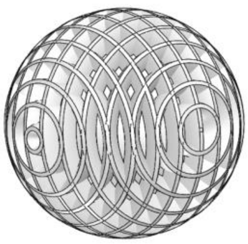


Fig.4.4(a) Spherical gear generation process diagram

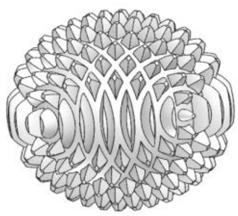


Fig.4.4(b) Spherical gear generation diagram

In the tooth ring, adjacent tooth rings together form the outer contour of a involute gear, and the outer sides of adjacent tooth rings are the meshing surfaces of the involute gear. Adjacent tooth rings have different numbers of teeth. When two spherical gears are connected together through core meshing, the back-to-back adjacent teeth on the two adjacent tooth rings do not interfere with each other, forming a new type of spherical gear.

4.3 The Generating Method of Monopole gear

To generate a monopole gear, the following steps are taken:

First, the relevant parameters of the monopole gear are determined based on the module and number of teeth of the spherical gear. The module is the same as the cylindrical gear module used in the spherical gear, m=2, and the number of teeth is half of the number of teeth in the spherical gear, z=16. The section of the spur gear is used as the boundary to stretch a cylinder, and the cylinder is pre-cut using the tooth root circle of the spherical gear to form the tooth blank of the monopole gear, as shown in Fig.4.5.

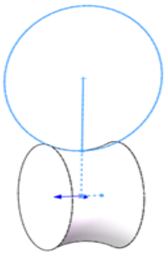


Fig.4.5 Monopole gear cylinder blank pre-excision

This monopole gear is produced using a processing method similar to that of gear hobbing. The spherical gear is rolled over the surface of the gear blank and the intersecting parts are cut off to obtain a monopole gear that matches the spherical gear. First, the gear blank is divided into 180 parts, then the basic spherical gear is revolved 2 degrees to the next division point while rotating 1 degree, and the operation is repeated to make the contour line of the basic spherical gear surround the conical surface for one full turn, thus forming a complete monopole gear.

V. Cam Massage Device

5.1 Principle of Cam Massage Mechanism

The motion law of the follower commonly includes polynomial motion law and harmonic combination motion law. The choice of follower motion law directly affects the quality of the cam mechanism during its design [6]. As shown in the schematic diagram of the cam massage mechanism in Fig.5.1, the cam is the driving component, and the rollers and massage claws are the driven components. When the cam is driven, it can drive the rollers and claws to massage the back of the neck. The cam massage part of the device is shown in Fig.5.2. The gray part at the front end of the claws is made of soft material, which can adaptively and softly fit the human neck for massage.

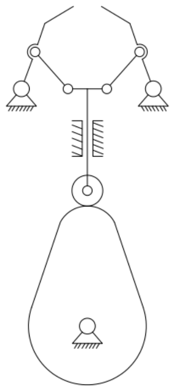


Fig.5.1 Schematic diagram of the cam massage mechanism

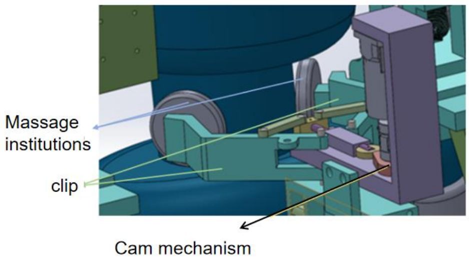


Fig.5.2 Schematic diagram of a cammassage device

Calculation of degrees of freedom for the cam massage mechanism: As shown in Fig.15, the number of moving links is 8, the number of higher pairs is P_h=1, and the number of lower pairs is P_l=6. Therefore, the degree of freedom of the cam massage mechanism is $F=3n-2P_l-P_h=3\times6-2\times8-1=1$.

5.2 Incorporating Acupressure Techniques Based on Traditional Chinese Medicine

The traditional Chinese cultural background and philosophical thinking have influenced the development of the medical thinking that guides the theory, diagnosis, treatment and prescription of Chinese medicine, under specific production modes, scientific levels and moral concepts[7]. In consideration of the multifunctional purposes of this device, in addition to actively training the muscles of the neck, it is necessary to incorporate neck massage function, to achieve better rehabilitation results and prevent muscle atrophy in the neck region. The main acupoints of the neck and back are Fengchi, Fengfu and Tianzhu[8], as shown in Fig.5.3. Massaging these acupoints has a good effect on relaxing the neck muscles. Moreover, for other diseases caused by cervical spine problems, such as lumbar disc herniation, headaches and dizziness, there are also significant therapeutic effects.

As depicted in Fig.5.2 the grey soft mechanism at the front end of the cam massage mechanism corresponds to the three acupressure points shown in Fig.5.1, which helps to achieve the massage effect.

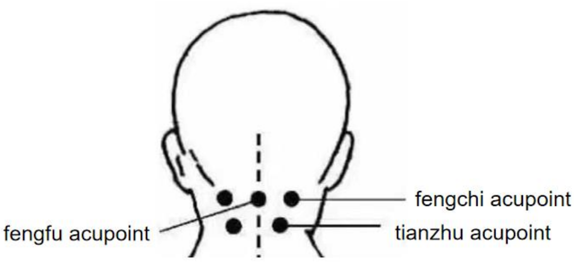


Fig.5.3 Main acupoint figure for the neck and back of the human body

VI. Exoskeleton-like Robot Mechanism control system

RS485 bus can control multiple slave stations with one master station, signal shielding effect is good, not easy to be interfered, solid device control system adopts RS485 signal transmission mode, built as shown in Fig.6.1 control schematic.

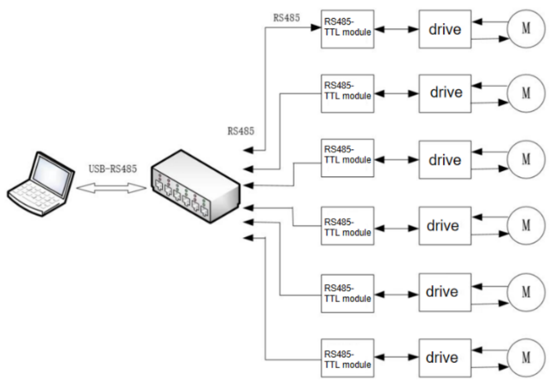


Fig.6.1 Schematic diagram of the control of exoskeleton-like robot mechanism

(1)The TTL signal is sent from the PC-side upper computer program and converted to a 485 signal, which is then output to the 485 hub to achieve the "one-to-many" control effect.

(2)Each 485 end of the conversion cable is connected to an RS485-TTL module to achieve data conversion, and then connected to the driver for real-time control of the motor.

In order to realize the movement required by the mechanism, the six motors of the rehabilitation training mechanism respectively realize the following functions: the motor M1 and M2 control mechanisms assist the head and neck swing; Motor M3 and M4 control mechanism assists head and neck pitch; The motor M5 control mechanism assists the head and neck rotation; The motor M6 control mechanism massages the neck.

VII. Conclusion

(1) Based on a biological analysis of the human body, a kinematic model was abstracted for the movement of the head and neck. The proposed 2-UPU spatial parallel and single R-series-parallel hybrid mechanism can perfectly assist in the movements of flexion, lateral bending, and rotation of the head, achieving the effects of neck rehabilitation and strengthening of neck muscles.

(2) Taking into consideration the comfort of the user, the accuracy of motion transfer, and the simplicity of control, the 2-UPU mechanism is symmetrically arranged on both sides of the neck to avoid obstructing the patient's line of sight, ensuring a comfortable fit for the user. The transmission system innovatively introduces the use of a spherical gear and a monopole gear, achieving decoupling of two degrees of freedom for rotational motion and intermittent motion transfer. In addition, the twisting motion of the mechanism is also decoupled from the flexion and lateral bending motion. The monopole gear and spherical gear transmission realize decoupling of flexion and lateral bending motion of the head, while the rotation of the spur gear realizes the twisting motion of the head. This design achieves precision motion transfer and a user-friendly control system.

(3) The designed exoskeleton-like robot mechanism is multifunctional. In addition to active rehabilitation training, a cam mechanism is designed to massage the Fengchi point, Fengfu point, and Tianzhu point, which can effectively relax the neck muscles.

(4) A stepper motor control system is designed, which sends serial port signals from the PC-side host to the motor controller chip to drive the exoskeleton-like robot mechanism, achieving assisted rehabilitation exercises and neck massage.

ACKNOWLEDGEMENTS

The author is grateful for the financial support provided by the Shanghai University Student Innovation Training Project (No. cs2201007) and Shanghai Collaborative Innovation Center of

Intelligent Manufacturing Robot Technology for Large Components (Grant No. ZXY20211101).

*Corresponding author: Lubin Hang, Email: hanglb@126.com

REFERENCES

[1]. Chen Chaofeng Theoretical analysis and design of ALS cervical exoskeleton based on spherical parallel mechanism [D]. Harbin Institute of Technology, 2016

[2]. Zhang H , Chang B C , Agrawal S . Using a Robotic Neck Brace for Movement Training of the Head-Neck[J]. IEEE Robotics & Automation Letters, 2019:1-1.

[3]. Haoyanyan. Modeling and analysis of cervical vertebrae and design of cervical exoskeleton [D]. Nanjing University of Science and Technology, 2009.

[4]. Yuan Chun, Ma Hongna, Liu Caixia, Cheng Ruijuan, Jia Qingyun. Analysis of the effects of cervical traction combined with cervical rehabilitation exercises on NDI and VAS scores in patients with cervical spondylosis [J]. Shenzhen Journal of Integrated Traditional Chinese and Western Medicine, 2022, 32(21):105-108.

[5]. Xu Zhenquan. Research on three-degree-of-freedom involute gear [D]. Changchun University of Science and Technology, 2020.

[6]. Chen Jiameng. Dynamic analysis and simulation of cam mechanism considering contact collision of flexible follower [D]. Tiangong University, 2021.

[7]. Xia Shujie, Lin Xuejuan, Lai Xinmei, Zhao Wen, Wei Jia, Wang Fengzhen, Li Candong. Literature research on the thinking mode and characteristics of traditional Chinese medicine [J]. Chinese Journal of Traditional Chinese Medicine, 2020, 35(04):2034-2037.

[8]. Hou Jianpeng, Wang Bolun, Liu Peng, Liu Jianwei, Gao Junhu, Guan Jichen, Han Xu, Sun Dongying. Effects of acupuncture combined with exercise therapy on the efficacy of cervical radiculopathy and blood rheology [J]. Acupuncture Research, 2022, 38(07):20-23.