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# Design of lower limb rehabilitation exoskeleton with self-adaptive knee optimal force

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**Abstract.** With the increasingly serious trend of population aging in China, various diseases of the elderly are emerging in an endless stream, including hemiplegia, half limb disorder, limb numbness, hemianopia, and aphasia, with a high disability rate. The available auxiliary device cannot make a clear assistance for the patient, so that this design plans to make an exoskeleton for the patients who need effective rehabilitation alternatives and improve the rehabilitation efficiency. In this design, we would create Solid works model with some joint to fit human knees and then select sensors which are suitable to collect signs to depict kinematics features. The model, which has self-adaptation for receiving force signs from calf and knee joint, depends on the different force points of the calf lift affecting the stress state of the knee joint. Because the different stress points of the calf lift directly affect the stress state of the knee, so to find the best stress point of the calf is the research direction of this paper. In order to find the best and the most suitable force point of the human lower limb, we two methods, step-by-step process and dichotomy process, were discussed and compared in this study. Reasonable material may decide the robotic features.

**Keywords:** lower limb exoskeleton, knee joint rehabilitation, knee joint force, self-adaptation, stress point.

## 1. Introduction

With the increasingly serious trend of population aging in China, various diseases of the elderly are emerging in an endless stream, including hemiplegia, half limb disorder, limb numbness, hemianopia, and aphasia, with a high disability rate. traditional rehabilitation methods for patients with lower limb paralysis and knee joint dysfunction can be resource-intensive and might not always yield optimal results. Following the demand for adapting to available classes of sensors, robot should achieve a remarkable degree in many aspects as comfort [1], flexibility and stability, and meanwhile, consider the value [2]. In recent years, due to the rapid development of science and technology, a large number of lower limb rehabilitation exoskeleton robots have been developed for the treatment of such patients. Compared with traditional methods, lower limb rehabilitation exoskeleton robot treatment has better dynamic repeatability and consistency.

The general medical robot needs accurate movement as it can be able to accomplish intrinsic operation, while medical exoskeleton robot movement as arthrogryposis requires co-operation with human body like fingers or knees. Some rehabilitation exoskeleton robots play an auxiliary role in helping the sick or the elderly recover from disability, and available exoskeleton robots, in disaster or medical rescues, need to be promoted for amplifying strength [3].

Additionally, with more serious conditions of patients suffered from spine injury or bad impact on knees through collision, there is a good choice if a partly-knee-based exoskeleton is available. There are too many exoskeletons for the whole lower limb rather than specially working for knees only, which may carry extra weight, and the intrinsic and complicated in too many sensors that may affect the whole robots' collaboration capacity in instable environment. The key point to address such an embarrassment is designing exoskeletons only for knees rehabilitation and strength enhancement. Making an effective Human-Machine Interaction routing with less sensors may put it to an end.

Among recent researches, many human finger exoskeletal-assisted ones named SUBAR [4] help develop the general humanoid skeletons. Beside general pressure-sensor-driving from human muscle robots, electrically operated robots controlled by neuro muscles as FES depending on muscular electric signs provide another approach. Including the module of electric methods for modern medical therapies like, on the basic of FES, a hybrid integrating robot makes the old model into a more stable one and make many times' innovations [5]. Others like a kind of hybrid exoskeleton with 4-link in bipedal waking system [6] or hybrid FES-exoskeleton with cooperative strategy designed for muscles recovery [7] have mature technologies about collecting electric sign and how to cope with it. In recent years, a type relying on surface on skins through sEMG Interface tech makes a great update to become lighter and more effective with more dexterity and mobility [3], which promotes the Elec-Mech technology in medical therapies. All of the researches make an improvement in exoskeletons for lower limb.

Instead, the weakness we get from the existing outcomes is lack of specially serving for knees with comfortability and dexterity designing. In market, it is obvious that most of lower limb exoskeletons are insufficient in parameter measurement in interaction, comfort rate. From different joints, the conditions make various effects and, among many exoskeletons for lower limb, there is no locked test to make sure that the security could work well. Through our design, we would find a new approach to develop to avoid disadvantages and design for a low-cost exoskeleton for knees. Here we illustrate some data through a table 1 with different figures (including security tests and comfort tests) the existing references have shown.

**Table 1.** Figures of available designs.

| Study | Assisted joint | Locked/Unlocked test | Comfort rated test |
|---|---|---|---|
| Wang et al., RAL | knee | No | No |
| Sarkisian et al., TNS | knee | Yes | Yes |
| Lee et al., TMECH | hip, knee, ankle | No | No |
| Wang et al., TMECH | knee | Yes | No |
| Chang et al., FRAI | hip, knee, ankle | No | No |

In this design, we would create physical model with some joint to fit human knees and then select sensors which are suitable to collect signs to depict kinematics features. Reasonable material may decide the robotic features (rigid/soft). After designing circuit in pneumatical or hydraulic controlling and in electronic, we would finally make a simple analysis in its walking stability.

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## 2. Methods and design

### *2.1. Solidworks model*

As an example, we introduce this design by an available exoskeleton model providing auxiliary function for knees joint (Sarkisian et al., 2021). The exoskeleton, which has 4 revolute pairs and 2 prismatic pairs, could be easily controlled and finish assistance tasks. The exoskeleton contains, in the part of thigh, straps fixing in both thigh and hip and a shell for protection, and, in the part of calf, a linear guide for knee joint vertical movement and straps with rotary joints fixing in calf.

In Figure 1, a schematic diagram of the exoskeleton is shown. The green rod driven by servo motor is combined with buffer reducer. The red indicator is on behalf of the force direction of the calf, that is, the direction of the pressure sensor. The sensor relying on vertical motion records different pressure of different position.

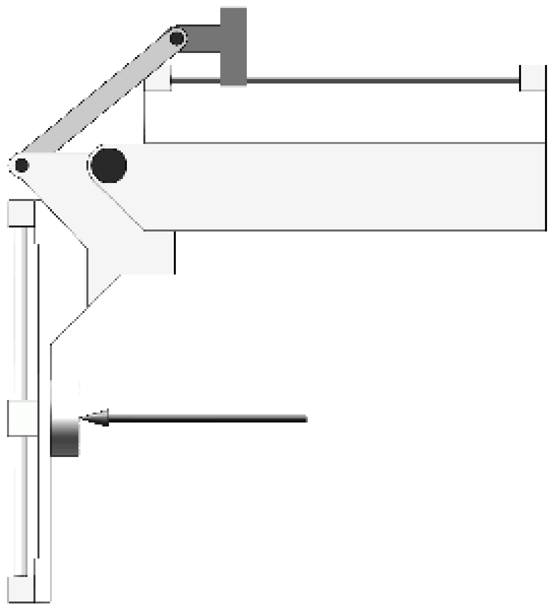

**Figure 1.** Schematic diagram and basic principle of its motion.

This work takes the exoskeleton to make a simple and explicit model which could be recognized as target to cope with in Solid works. Figure shows a type of physical model made by SolidWorks, with two respective parts of thigh and calf.

Both of the 2 parts have components, connecting with straps or bands, for fixation on knees. The function based on supporting the knee structure and transferring power constitutes the fundamental part of the exoskeleton.

The main point in calf part including a guide and a slide make the power transfer into calf and assist for movement of the user’s knee flexion and extension and then help control walking or other motion relying on this part. Figure3 exhibit the guide and the slide.

This work finally have the whole models for respective 2 parts. In the section of thigh, the mechanism is driven by the connecting rod ahead. When power is transferred to the groove rod and then to the calf part. Fixed in a plate element, the guide and the slide receive the power transferred through the basic component, and the slide make the end for a whole kinematic circuit. Two parts give a whole presence in Figure 2. In this figure, we make a simplified model with 3 pDOFs. This model aims for showing the frame of this study.

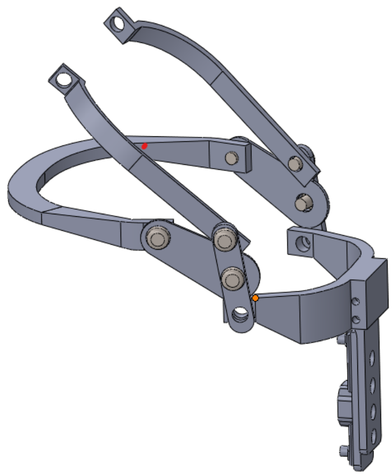

**Figure 2.** Assembled model for the exoskeleton.

In Figure 3, we make the whole model of the exoskeleton. In the detailed model design process, in addition to the servo motor, the buffer reducer could prevent the device from skidding when the power conveying belt is under too much force, and could increase torque. We give up the cortical straps and innovatively design the coating structure with carbon fiber board and air bags instead. This part would be driven by micro air pump, which could possibly reduce the whole weight and make improve comfort.

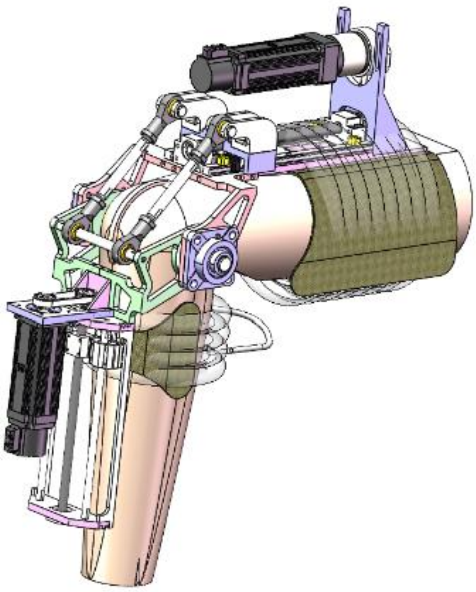

**Figure 3.** The assembled model.

The model is driven by a linear-and-rotary motor, and the power forces on the top connection rod. In the process of walking or simple joint rehabilitation, the exoskeleton is bond with air bags in both of thigh and calf. Additionally, in calf straps, an extra strap connecting with main board assist for more flexibility in revolute pair. To present how the exoskeleton runs rehabilitation tasks, a lower limb model, containing thigh, calf and knee joint only, is provided for motion simulation, which, with straps designed ahead. While, in practical motion, the motor gives a power resource to the exoskeleton, the rod would drive other rods rotate so that move the calf part. The calf part would turn rotation into vertical motion to assist calf to rise or fall, and then drive knee joint straightening or bending. The condition of straightening is shown in Figure 4.

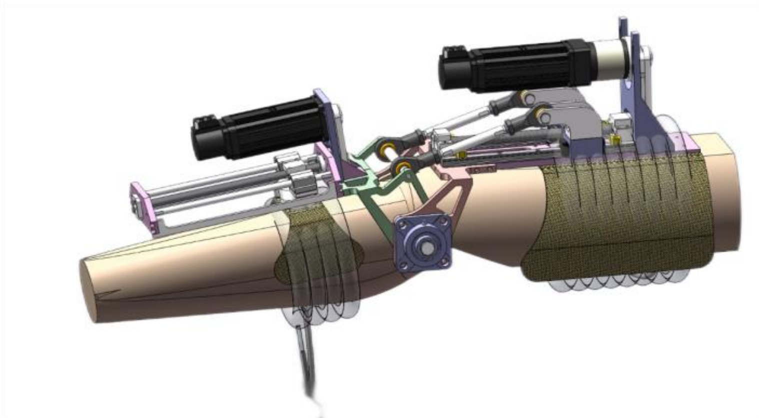

**Figure 4.** Knee joint straightens with lower limb model.

The pressure sensor, to have a self-adaptation capacity, would be used for searching for the most suitable pressure on the calf. The exoskeleton needs to find the minimum force point to automatically adapt patients' different pressure points. We define the "position making the knee in the process of lifting the calf by the minimum force" as the best force point, and, in the design, the pressure sensor automatically finds the best force point through vertical motion in the trapezoidal screw. Before each pressure sensor moves up and down, the airbag needs to be deflated to disengage from the calf. When the leg needs to be lifted, it needs to be inflated to make the air bags hold the calf.

The two methods of motion of pressure sensor, step-by-step process and dichotomy process, both need coordinate system based on the knee joint and its coordinate changes. Step-by-step process, along a direction, equidistant mining points, and finally gets the minimum point which is the best force point. The starting position of the best force point is the best force point function plus a given deviation value. Dichotomy process is that, according to the minimum coordinate given by the best force point function, plus a deviation, continuous dichotomy in the range of deviation, the final value is the best force point.

Supposing that the optimal force point measured by a normal person is at a position of 105 mm, we decide that the deviation value was selected as 20 mm, and the point of [85,125] mm was taken for measurement and would respectively discuss the different progress of the two methods. In the step-by-step process, we chose 5mm as a step size, and the supposed height is divided into 9 points, and record the different pressure value. Table 2 is designed for the value collection, and the final measured value would be placed in the blanks Pressure Value. Considering dichotomy process, in the first dichotomy we take the points 95 and 115 in the middle of [85,105], [105,125]. If the measured value of 95 is less than 115, [95,105] is selected as the new interval, that is, the interval where the best force point may appear. In the second dichotomy, we take the points 97.5 and 102.5 in the middle of [95,100], [100,105]. If the measured value of 97.5 is less than 102.5, then select [ 97.5,100] as the new interval. We suppose that the iteration times would reach 'n'. When the number of iterations reaches the end of the iteration, the final interval is the possible interval, and the intermediate value of this interval is the best force point. The experimenter weighed 70kg. The bending degree of knee joint was 135 degrees (based on the thigh).

**Table 2.** Pressure value collection

| Collection number | Collection coordinate | Pressure value(N) |
|---|---|---|
| 1 | 85 | 240.1 |
| 2 | 90 | 227.7 |
| 3 | 95 | 200.2 |
| 4 | 100 | 165.5 |
| 5 | 105 | 133.8 |
| 6 | 110 | 111.4 |
| 7 | 115 | 102.9 |
| 8 | 120 | 140.7 |
| 9 | 125 | 181.8 |

To compare the two methods, we would eventually record the value of coordinate and chose the one method having more accurate data in coordinate and determine the method. In table 3, the motor power value, pressure sensing value and coordinates are selected as parameter variables, and we compared the coordinate accuracy between the two methods. Having decided that the power value and different pressure sensing value in quantitative groups, we finally choose dichotomy process.

**Table 3.** The comparative experiment and data analysis of two methods.

| Groups | Step-by-step process | Dichotomy process |
|---|---|---|
| 1 | 85 | 86.25 |
| 2 | 90 | 91.25 |
| 3 | 95 | 95 |
| 4 | 100 | 98.75 |
| 5 | 105 | 105 |
| 6 | 115 | 116.25 |
| 7 | 125 | 123.75 |

### *2.2. Kinematic model analysis*

The kinematics of exoskeleton robot mainly includes two aspects: the first aspect: knowing the relative position parameters and joint variable parameters of the robot bar, solving the position, velocity, acceleration and posture of the end effector relative to a given coordinate system, and the solved parameters are called forward kinematics; the second aspect: knowing the position, velocity, acceleration and posture of the end effector, solving the joint parameters of the robot, and the solved parameters are called inverse kinematics.

The kinematics equation of the exoskeleton robot of the rehabilitation machine is the position and posture of the robot end relative to the reference coordinate system, and the known conditions are the length of the thigh and calf rods of the robot and the rotation angle vector of the medullary joint and knee joint. Because the mechanical structure and motion mode of the left and right sides of the rehabilitation exoskeleton robot are exactly the same, but there is a difference in time, the research on the whole robot can be simplified to the research on the mechanism on one side of the robot. According to the D-H method, a kinematic analysis coordinate system is established on each joint of the right mechanism, as shown in Figure 5, and the D-H parameters of the robot are shown in Table 4. The homogeneous transformation method can accurately describe the relative positions and postures of the coordinate systems. Since the coordinate system is set on the joints, the relationship between the right connecting rods can be described, and the postures of the joints can be obtained.

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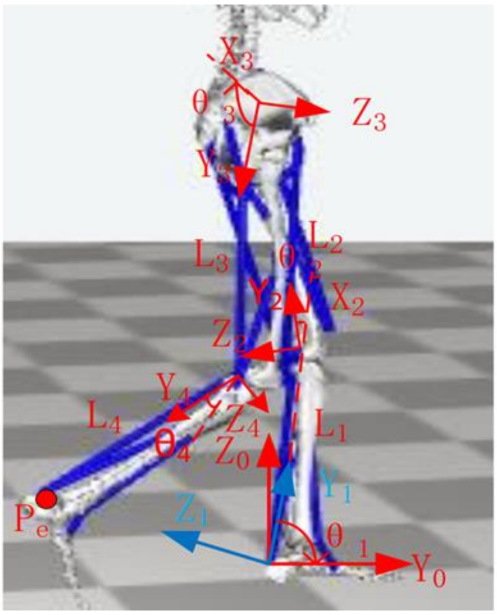


[19]

**Figure 5.** Joint coordinate system.

**Table 4.** Parameter table of connecting rod.

| i | $\alpha_{i-1}$ | $a_{i-1}$ | $d_i$ | $\theta_i$ |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | θ1 |
| 2 | 0 | L1 | 0 | θ2 |
| 3 | 0 | L2 | 0 | θ3 |
| 4 | 0 | L3 | 0 | θ4 |

$$ {}_1^0T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_1 & -\sin\theta_1 & 0 \\ 0 & \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

[19]

$$ {}_1^0T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_1 & -\sin\theta_1 & 0 \\ 0 & \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

$$ {}_2^1T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_2 & -\sin\theta_2 & L_1 \\ 0 & \sin\theta_2 & \cos\theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2) $$

$$ {}_3^2T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_3 & -\sin\theta_3 & L_2 \\ 0 & \sin\theta_3 & \cos\theta_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3) $$

$$ {}_{4}^{3}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_3 & -\sin\theta_3 & L_3 \\ 0 & \sin\theta_3 & \cos\theta_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4} $$

The transformation matrix from the coordinate system {i }(i ≥2) to the coordinate system {0} can be obtained by performing the "×" operation of the matrix in the formulas (1)(4) in turn.

$$ {}_{2}^{0}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\left(\sum_{i=1}^{2}\theta_i\right) & -\sin\left(\sum_{i=1}^{2}\theta_i\right) & L_1\cos\theta_1 \\ 0 & \sin\left(\sum_{i=1}^{2}\theta_i\right) & \cos\left(\sum_{i=1}^{2}\theta_i\right) & L_1\sin\theta_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

$$ {}_{3}^{0}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & a_{22} & a_{23} & a_{24} \\ 0 & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6} $$

In the formula (6):

$$ a_{22} = (\cos\sum_{i=1}^{3}\theta_i) a_{23} = -\sin\sum_{i=1}^{3}\theta_{\mathrm{i}} $$

$$ a_{24} = L_1(\cos\theta_1) + L_2(\cos\sum_{i=1}^{2}\theta_i) a_{32} = \sin\sum_{i=1}^{3}\theta_i $$

$$ a_{33} = (\cos\sum_{i=1}^{3}\theta_i)\ a_{34} = L_1(\sin\theta_1) + L_2(\sin\sum_{i=1}^{2}\theta_i) $$

$$ {}_{4}^{0}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & b_{22} & b_{23} & b_{24} \\ 0 & b_{32} & b_{33} & b_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7} $$

In the formula (7):

$$ b_{22} = (\cos\sum_{i=1}^{4}\theta_i) b_{23} = -\sin\sum_{i=1}^{4}\theta_i $$

$$ b_{24} = L_1(\cos\theta_1) + L_2(\cos\sum_{i=1}^{2}\theta_i) + L_3(\cos\sum_{i=1}^{3}\theta_i) $$

$$ b_{32} = (\sin\sum_{i=1}^{4}\theta_i) b_{33} = \cos\sum_{i=1}^{4}\theta_i $$

$$ b_{34} = L_1(\sin\theta_1) + L_2(\sin\sum_{i=1}^{2}\theta_i) + L_3(\sin\sum_{i=1}^{3}\theta_i\ ) $$

The posture of the swinging leg end on the lower limb exoskeleton in the spatial coordinate system {0} can be obtained from the formulas (1) - (7). The forward kinematics analysis of the lower limb exoskeleton that is based on the D-H parameter is as follows:

$$ {}^{0}p_e = {}^{0}_{4}T\,{}^{4}p_4 = {}^{0}_{4}T \begin{bmatrix} 0 \\ L_4 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ L_1(\cos\theta_1) + L_2(\cos\sum_{i=1}^{2}\theta_i) + L_3(\cos\sum_{i=1}^{3}\theta_i) + L_4(\cos\sum_{i=1}^{4}\theta_i) \\ L_1(\sin\theta_1) + L_2\left(\sin\sum_{i=1}^{2}\theta_i\right) + L_3\left(\sin\sum_{i=1}^{3}\theta_i\right) + L_4\left(\sin\sum_{i=1}^{4}\theta_i\right) \end{bmatrix} \tag{8} $$

[19]

## 3. Results

By importing the model and parameters into MATLAB, we can obtain the following calculation results in Figure 6. The simulation model result in MATLAB was shown in Figure 7. The lower axis in provided parameters make consistent trajectory with expectation through simulating knee joint rotation.

```
robot =

modified sawyer:: 2 axis, RR, modDH, slowRNE
+---+-----------+-----------+-----------+-----------+-----------+
| j |     theta |         d |         a |     alpha |    offset |
+---+-----------+-----------+-----------+-----------+-----------+
|  1|         q1|          0|          0|          0|          0|
|  2|         q2|     0.1925|      0.081|    -1.5708|          0|
+---+-----------+-----------+-----------+-----------+-----------+
```

**Figure 6.** Calculation results of the given parameters.

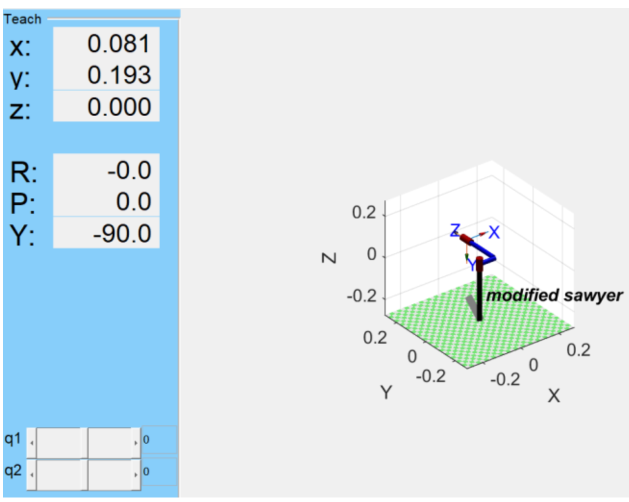


**Figure 7.** The MATLAB results of the kinematic model.

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## 4. Conclusion

The knee rehabilitation under the best stress state is effective, which can effectively improve the efficiency of knee rehabilitation and reduce the secondary injury of the knee caused by the unintelligent rehabilitation equipment during the rehabilitation process. Help can be appropriately reduced. Through experiments, it can be known that the efficiency of the dichotomy method to find the best force point will be higher than that of the stepping method, and the best force point will be found more accurately, and the number of detections required will be less. Through experiments, it can be known that the efficiency of the dichotomy method to find the best force point will be higher than that of the stepping method, and the best force point will be found more accurately, and the number of detections required will be less. In this design, we take the following two points as the innovation. First, the concept of the best force point is proposed, and the best force point can effectively improve the efficiency of knee rehabilitation. A device and method are also designed to automatically detect and find the best force point. It improves the automation and intelligence of rehabilitation medicine. In additional, the exoskeleton of this design uses an air bag to cover the legs, and a micro air pump is used as the air bag's charging and discharging device. Effectively fit the leg structure of the person, which is more comfortable and convenient than the strap. In the process of automatic adjustment, there is no need for manual adjustment.

### Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

### References


[1] Sarkisian SV, Ishmael MK, and Lenzi T. Self-Aligning Mechanism Improves Comfort and Performance with a Powered Knee Exoskeleton [J]. IEEE Transactions on neural system and rehabilitation engineering. 2021, 29:629-640.

[2] Seminara L, Gastaldo P, Watt SJ, Valyear KF, Zuher F, and Mastrogiovanni F. Active Haptic Perception in Robots: A Review. Frontiers in neurorobotics, 2019, 13.

[3] Wang C, Guo Z, Duan S, He B, Yuan Y, and Wu X. A Real-Time Stability Control Method Through sEMG Interface for Lower Extremity Rehabilitation Exoskeletons. Frontiers in neuroscience, 2021, 15.

[4] Kang CJ, Chun MH, Lee J, and Lee JY. Effects of Robot (SUBAR)-assisted Gait Training in Patients with Chronic Stroke: Randomized controlled trial. Medicine (Baltimore), 2021, 100(48).

[5] Resquín F, Gonzalez-Vargas J, Ibáñez J, et al. Adaptive hybrid robotic system for rehabilitation of reaching movement after a brain injury: a usability study. J Neuroeng Rehabil, 2017, 14(1):1 04.

[6] Chang CH, Casas J, Brose SW, and Duenas VH. Closed-Loop Torque and Kinematic Control of a Hybrid Lower-Limb Exoskeleton for Treadmill Walking. Frontiers in robotics and AI. 2022, 18.

[7] Del-Ama AJ, Gil-Agudo A, Pons JL, and Moreno JC. Hybrid FES-robot Cooperative Control of Ambulatory Gait Rehabilitation Exoskeleton. J Neuroeng Rehabil, 2014, 11(27).

[8] Zhang M. Research on Motion Control Strategy of Lower Limb Exoskeleton of Rehabilitation Robot [D]. Liuzhou: Guangxi University of Science and Technology, 2020.

[9] Zhang D. Research on Control System and Control Strategy of Lower Limb Rehabilitation Robot [D]. Qinhuangdao: Yanshan University, 2016.

[10] Chen G, LI C, and LIU G. Research on Adaptive Control of Lower Limb Exoskeleton Rehabilitation Robot [J]. Manufacturing Automation, 2012, 34(24):5-9.

[11] Li G, SI G, and Xu F. Research Progress of Lower Limb Exoskeleton Robot Control Strategy [J]. Chinese Journal of Rehabilitation Medicine, 2018, 33(12):1488-1494.

[12] Yang L, and Hu J. Research on Convergence of iterative Learning Algorithm Based on Optimal Control [J]. Mechanical and Electrical Engineering, 2018, 35(4).

DOI: 10.54254/2755-2721/35/20230387

[13] Ma H, and Liao WH. Human Gait Modeling and Analysis Using a semi-Markov Process with Ground Reaction Forces[J]. IEEE Transactions on Neural Systems & Rehabilitation Engineering, 2017, 25(6):597 -607
[14] LIM D, KIM W, and KIM H. Development of real-time gait phase detection system for a lower extremity exoskeleton robot [J]. International Journal of Precision Engineering and Manufacturing, 2017, 18(5):681-687.
[15] Yu L, Zheng J, Wang Y, Song Z, and Zhan E. Adaptive method for real-time gait phase detection based on ground contact forces[J]. Gait & Posture,2015, 41(1):269-275.
[16] Kennard M, Kadone H, Shimizu Y, and Suzuki K. Passive Exoskeleton with Gait-Based Knee Joint Support for Individuals with Cerebral Palsy. Sensors (Basel, Switzerland), 2022, 22(22).
[17] Hussain F, Goecke R, and Mohammadian M. Exoskeleton robots for lower limb assistance: A Review of Materials, Actuation, and Manufacturing Methods. Proceedings of the Institution of Mechanical Engineers. Part H, Journal of engineering in medicine, 2021, 235(12): 1375-1385.
[18] Bryan GM, Franks PW, Song S, et al. Optimized Hip-knee-ankle Exoskeleton Assistance at a Range of Walking Speeds. Journal of neuroengineering and rehabilitation, 2021, 18(1).
[19] Liu Kun. Research and Application on Walking Stability of Lower limb Exoskeleton Robot [J] Qufu Normal University, 2020 (4); 22-1