ISSN 2278-3091
Volume 8, No.1.1, 2019
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse5881.12019.pdf
https://doi.org/10.30534/ijatcse/2019/5881.12019

Design and Analysis of a Spatial Four-DOF Lower Limb Rehabilitation Robot

Hongbo Wang Yongfei Feng[1], Xincheng Wang[1], Lingxue Ren[1], Jianye Niu[1], and Luige Vladareanu[2*]
[1]Parallel Robot and Mechatronic System Laboratory of Hebei Province and
Key Laboratory of Advanced Forging & Stamping Technology and Science of
Ministry of Education, Yanshan University, Qinhuangdao, 066004, China
Hongbo_w@ysu.edu.cn , yf_feng@126.com

[2*]Robotics and Mechatronics Department,
Institute of Solid Mechanics of the Romanian Academy, 010141, Bucharest, Romania

ABSTRACT

Aiming at the existing problem that the majority of lower limb rehabilitation robots can only realize patient's leg to move in the sagittal plane, cannot achieve the patient's leg to move in coronal plane, a spatial four-DOF multi-pose lower limb rehabilitation robot is proposed. The robot could also realize the sitting training posture, the lying training posture and the standing training posture. The robot includes seat, left mechanical leg and right mechanical leg. Each mechanical leg with series-parallel mechanism includes the hip joint with two DOFs, knee joint with one DOF and ankle joint with one DOF which correspond to the hip joint, knee joint and ankle joint of human. This paper describes the mechanical design and kinematic analysis of the rehabilitation robot. The coordinate system of the lower limb rehabilitation robot is established, and the degree of freedom of the spatial leg mechanism is calculated. The inverse kinematics of the single leg mechanism and the forward kinematics of the lower limb rehabilitation robot are analyzed. The workspace of the leg mechanism was calculated. The kinematics analysis of the leg mechanism lays a theoretical base for the future controlling of the robot prototype.

Key words : Lower Limb Rehabilitation Robot; Mechanical Design; Series-Parallel Mechanism; Kinematics

1. INTRODUCTION

Rehabilitation robot, as an auxiliary medical tool, helps people with limbs disability to recovery motor function, and helps patients to do scientific, reasonable, effective training under the guidance of the theory in medicine, and helps patients to live independently as soon as possible. Rehabilitation robot has brought the hope to patients with limbs disabled and therapists. At present, the lower limb rehabilitation robot is now a research hotspot, and few restoration robots have reclamation robots have been structured as the ask about achievement [1-6]. The commended recuperation robot structure LOKOMAT which was asked about by the Swiss Government Established of Innovation Zurich used suspension device to reinforce or modify human weight, and the calm may do bring down extremity walking walk reclamation getting ready with the help of outside forces [7]. Wang Xiaonan, et al proposed a suspended rebuilding mentor and a patient-driven control technique to goad the understanding participation [8]. The other rebuilding robot LOPES [9-10] consolidated an energetically exchangeable and two dimensional (2D)-activated pelvis partition with a leg exoskeleton containing three impelled rotational joints. The most work of LOPES was to displace the physiotherapists' mechanical cooperation with patients, though taking off clinical decisions to the judgment of the counselors. Carleton College made a virtual walk reclamation robot (ViGRR) for out of commission stroke patients. It can give the normal walk movement preparing just as other focused on activities, for example, leg press, stair venturing and persuasive gaming [11]. Yaskawa Electric Corporation of Japan designed a lower- rehabilitation robot, TEM LX2 type D [12], which was mostly utilized for patients with lower appendage ailment in an intense stage. Its fundamental reason for existing was to empower the patients to reestablish their physical capacities and walking capacity. Numerous intelligent control interfaces based on advanced control strategies and human adaptive mechatronics [13-14], have been developed. Swortec organization built up a most progressive sitting lower rehabilitation recovery preparing robot MotionMaker [15]. The framework is made out of two system leg involving engines and sensors, and a control unit dealing with the trans-cutaneous electrical muscle incitement with continuous guideline.

At present, most of the majority of lower limb rehabilitation robots can only realize the rehabilitation exercise in the sagittal plane [16]. In addition, the lower limb rehabilitation robots have three training postures, which are the standing training posture, the sitting training posture and the lying training posture. The sitting and lying training postures are suitable for the patients in early recovery stage. The standing training posture fits patients in the middle and later recovers stages. In view of the importance of the exercise with spatial motion with three training postures, a rehabilitation robot with four DOFs is proposed in this paper. The work is structured as follows. In section 2, the framework of the rehabilitation robot is explained. In section 3, the DOF, the kinematics and the workspace are investigated.

2. THE ANALYZE OF THE PATIENT LOWER LIMB PHYSIOLOGICAL PARAMETERS

To realize the spatial rehabilitation training of the proposed robot, including the motions in sagittal plane and coronal plane, the patient lower limb physiological parameters are analyzed. Based the principles of bionics, the motions of the hip joint are simplified into two degree of freedom motions through two perpendicular revolute pairs. The knee joint has a degree of freedom motion and the ankle joint has a degree of freedom motion. The simplified motion model of the patient lower limb is shown in Figure.1, which could satisfy the patient daily activities.

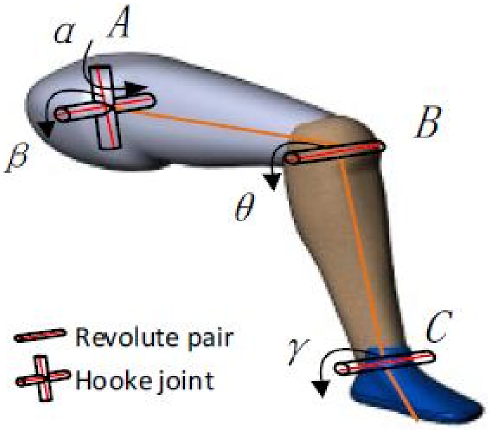


Figure 1: The simplified motion model of the lower limb

The joints of the normal people lower limb have a range of motion. Beyond the joint limits, the patient joint would be leaded a secondary damage. Meanwhile, joints of the normal people body always move in the comfortable motion ranges. It is meaningful to confirm the joint motion ranges for different patients to use. Based on the individual differences and the training postures (including sitting posture, lying posture and standing posture), the joint motion ranges are listed in Table 1.

Table 1: The joint motion ranges of the robot

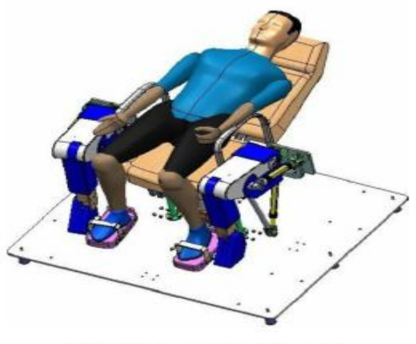
Joints	***Motion ranges***
Hip joint in sagittal plane	-15° ~ 110°
Hip joint in coronal plane	-20° ~ 20°
Knee joint in sagittal	–145°
Ankle joint in sagittal	–50°

As per anthropometry parameters and the design principles of an adjustable range, the thigh length range of the robot mechanism leg is 402~532mm. The calf length range of the robot mechanism leg is 313~421mm. However, the foot part is designed with a fixed value 80mm.

3. THE REHABILITATION ROBOT

The structure graph of the lower rehabilitation restoration robot with spatial four DOFs is exhibited in Figure 2. The robot incorporates: situate, left mechanical leg, and right mechanical leg, each mechanical leg incorporates the hip joint with two DOFs, knee joint with one DOF and lower leg joint with one DOF which relate to the hip joint, knee joint and lower leg joint of human.

(a) The sitting posture of the robot



(b) The lying posture of the robot

(b) The standing posture of the robot

Figure 2: Structure diagram of the robot

Both the mechanism legs are installed on the seat. By adjusting the seat angle, the patient can do the rehabilitation training in different postures: sitting posture, standing posture and lying posture. The structure of the seat is shown in Figure 3.

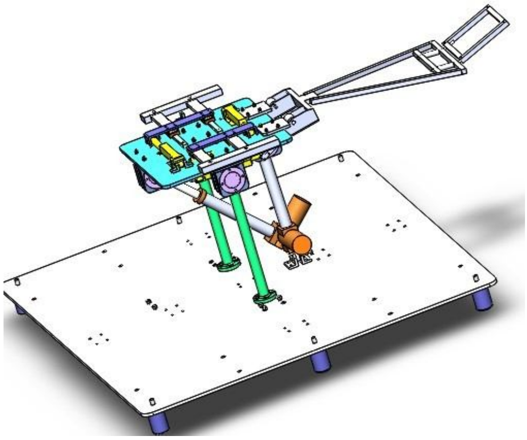


Figure 3: The structure of the seat

The robot is a spatial four-DOF lower limb rehabilitation training device which has the capacity of the dynamic preparing helped preparing and inactive preparing. The helped restoration preparing can be done agreeably by the joint torque sensor, the foot and leg weight sensor that can anticipate the human lower appendage movement goal. In any case posture of the human upper body changes with the rise of the seat, as far as possible position of human thigh additionally changes. The creative structure which the mechanical furthest reaches of the hip joint can be changed by the seat pitch point can make restoration preparing securely on the sitting stance or self-assertive lying stance. In addition, the seat pitch edge can be changed in accordance with meet the necessities of patients with various stances.

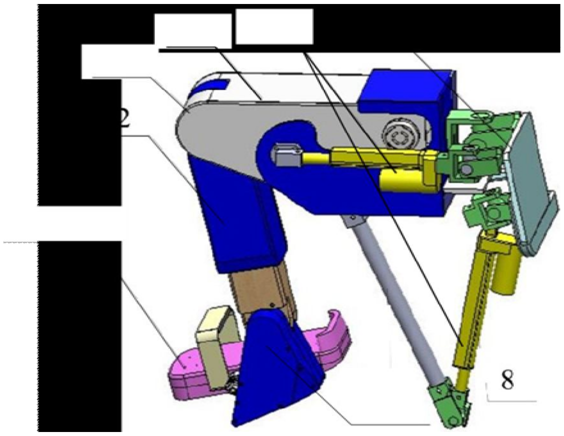


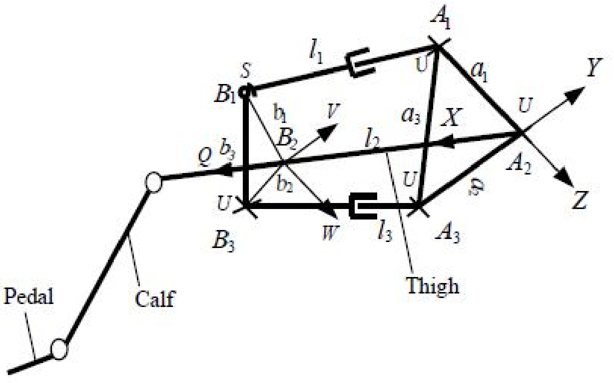
Figure 4: Structure diagram of the mechanical leg

Figure 4 represents the structure diagram of mechanism leg. To guarantee the safety of patients, the mechanical limit point of the hip joint is intended to be variable. At the point when the patients sit on the seat, the recovery doctors can control the activity interface to modify the length of the thigh and calf of the mechanical leg and the width between two mechanical legs. This can meet the prerequisites of various sizes of patients. At that point as per the wounds dimension of patients, the recovery preparing errands are set to finish the treatment of patients.

4. KINEMATIC ANALYSIS OF REHABILITATION ROBOT

4.1 Coordinate establishment of the lower limb rehabilitative robot

Mechanical leg of the lower limb rehabilitation robot is used for rehabilitation training of patients, so it is the main component of the robot. Figure 5 is the $\angle A_1A_2A_3 = 90°$, A_2B_2 represents the thigh, B_2 is fixed to a platform in the thigh, $\angle B_1B_2B_3 = 90°$. Coordinate system is established as follows: the fixed coordinate frame $A_2 - XYZ$ is established at point A_2 on the upper platform, Axis Y is parallel to A_2A_3, Axis Z is parallel to A_1A_2, and axis X is determined by the right-hand screw rule. The moving coordinate frame $B_2 - QVW$ is fixed at point B_2. Axes Q, V, W are respectively same to the axes X, Y, Z in the fixed coordinate frame $A_2 - XYZ$. According to Figure 2, some structural parameters are defined as follows: $a_1, a_2, a_3, b_1, b_2, b_3$ are some structural parameters of the upper platform and the lower platform. l_1, l_2, l_3 are the length of parallel mechanism three chains.



structure sketch of the mechanical leg which clearly shows the: hip platform is a right triangle,

Figure 5: Structure sketch of the mechanical leg

4.2 Coordinate establishment of the lower limb rehabilitative robot

This robot is series-parallel hybrid mechanism, so it is divided into two parts to calculate the DOF: the parallel part and series part. Compared with the parallel part, series part DOF is simple. The series part is composed of the knee and ankle joints, so it has four DOF. Mostly parallel mechanism is more difficult to analyze DOF, so based on the modified *Kutzbach-GR*`` formula, using the constraint screw to solve the mechanism DOF.

$$M = d(n-g-1)+\sum_{i-1}^{g} f_i + v - \xi \qquad (1)$$

The modified *Kutzbach-GR*`` formula is

Because the UPS branch cannot constitute constraints to the moving platform, so do not have to analyze the branched-chain. Therefore only analyzing the motion spiral of UPU branch and U branch, we can solve public constraint number and redundant constraint number. As shown in Figure 2, each movement pair spiral can be expressed as: Hooke hinge is converted to two independent rotations, and there are two spirals; moving pair has a spiral.

The UPU branch movement spiral system is:

$$\begin{aligned}
&\$_{U11}=(0\ 1\ 0;0\ a_2\ 0);\ \$_{U12}=(0\ 0\ 1;0\ a_2\ 0)\\
&\$_{p}=(0\ 0\ 0;\ \cos\theta_1\ \sin\theta_1\ 0)\\
&\$_{U21}=(0\ 0\ 1;\ c_1\ c_2\ 0)\\
&\$_{U22}=(\cos\theta_2\ \sin\theta_2\ 0;\ c_1\ c_2\ 0)
\end{aligned} \qquad (2)$$

The U branch movement spiral system is:

$$\$_{U11}=(0\ 1\ 0;0\ 0\ 0);\qquad \$_{U12}=(0\ 0\ 1;0\ 0\ 0) \qquad (3)$$

The anti-spiral system of UPU branch movement spiral system is:

$$\$_1^r=(0\ 0\ 1;0\ 0\ 0) \qquad (4)$$

It can be seen that this branch limits the Z-axis movement. The anti-spiral system of UPU branch movement spiral system is:

$$\begin{aligned}
&\$_1^r=(1\ 0\ 0;0\ 0\ 0);\quad \$_2^r=(0\ 1\ 0;0\ 0\ 0)\\
&\$_3^r=(0\ 0\ 1;0\ 0\ 0);\quad \$_3^r=(0\ 0\ 0;1\ 0\ 0)
\end{aligned} \qquad (5)$$

It can be seen this branch limits the movement of X, Y, and Z axes and rotation around the Z axis. According to the equation (4) and (5), UPU branch and U branch chains have a common anti-spiral $\$_1^r=(0\ 0\ 1;0\ 0\ 0)$, that is, these two branches common contains more about Z axis, so they have a redundant constraint:

$$t=2, k=1, \text{then } v=t-k=1$$

Because UPS branch doesn't provide constraint, so the mechanism has no public constraint: $\lambda = 0$, d = 6, n = 6, g = 7, ζ= 0, then

$$M = d(n-g-1)+\sum_{i-1}^{g} f_i + v - \xi = 2$$

Based on two-DOFs parallel part and two-DOFs series part, we can obtain the lower limb rehabilitation robot is four DOFs.

4.3 Coordinate establishment of the lower limb rehabilitative robot

When fixed coordinate system and moving coordinate system of static and moving platforms of UPS-UPU-U parallel mechanism coincide, the turning round of the moving platform around the static platform is equivalent to the rotation of moving coordinate system B_2-QVW around the Y axis and Z axis of fixed coordinate system A_2-XYZ. Suppose firstly rotating α angle around W axis of moving coordinate system B_2-QVW, then rotating β angle around V axis of the fixed coordinate system A_2-XYZ, then a rotation matrix about moving coordinate system can be obtained:

$$R = Rot(w,\alpha)Rot(v,\beta)=\begin{pmatrix} c\beta c\alpha & -s\alpha & c\alpha s\beta \\ c\beta s\alpha & c\alpha & s\beta s\alpha \\ -s\beta & 0 & c\beta \end{pmatrix} \qquad (6)$$

Where, $c\alpha=\cos\alpha$, $s\alpha=\sin\alpha$, $c\beta=\cos\beta$, $s\beta=\sin\beta$. To establish the mechanism position constraint equation in the fixed coordinates {A_2}, it is expressed as:

$$\begin{aligned}
&l_2 = l_2 q_2\\
&l_2 = m_i + l_i q_i - R n_i \qquad i=1,3
\end{aligned} \qquad (7)$$

where, l_i,$\boldsymbol{q}_i$ respectively represent the each branch rod length and unit vectors.

By the formula (6) and (7) we can obtain:

$$\alpha=\begin{cases}\arctan\left(\dfrac{q_y}{q_x}\right) & \alpha\le 90^\circ\\ \pi\text{-}\arctan\left(\dfrac{q_y}{q_x}\right) & \alpha\ge 90^\circ\end{cases}\qquad \beta=-\arcsin\left(\frac{q_z}{l_2}\right) \tag{8}$$

$$l_2=\sqrt{{q_x}^2+{q_y}^2+{q_z}^2}=306$$

Where qx, qy, qz are are various components of the U branch unit vector $\boldsymbol{q}_2$ in the fixed coordinate system$\{A\}$.

According to formula (6), (7) and (8), we can obtain the length of the other branches:

$$l_1=\sqrt{\left(q_x\text{-}c_1\cos\alpha\sin\beta\right)^2+\left(q_y-c_1\sin\alpha\sin\beta\right)^2+\left(a_1+q_z-c_1\cos\beta\right)^2}$$

$$l_3=\sqrt{\begin{array}{l}\left(q_x+d_1\cos\alpha\cos\beta+d_2\sin\alpha\right)^2+\left(a_2+d_1\cos\beta\sin\alpha+q_y-d_2\cos\alpha\right)^2\\+\left(q_z-d_1\sin\beta\right)^2\end{array}} \tag{9}$$

From the above analysis, parallel part has two DOFs that are the left and right swing β and up and down swing α of the hip joint (sitting position), so the parallel part can be simplified to rod OA with two swings. For the lower limb rehabilitation robot, it can be simplified to serial mechanism. It includes a thigh OA has two swings α, β, a calf AB has one swing φ, and a pedal BC has one swing γ. The model is described in figure 4.

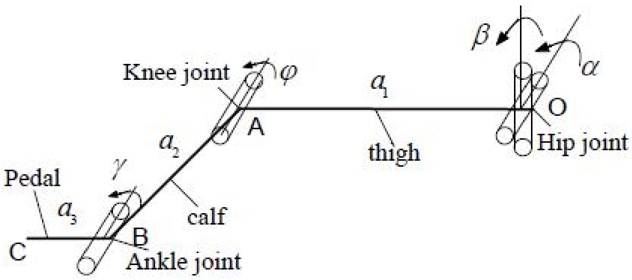


Figure 6: Simplified model of the machine

Inverse solution of the simplified machine can be written as follows:

$$\begin{cases}\alpha=\arccos\dfrac{x_B^2+z_B^2+y_B^2+a_1^2-a_2^2}{2l_1\sqrt{x_B^2+y_B^2+z_B^2}}+\arctan\dfrac{y_B}{\sqrt{x_B^2+z_B^2}}\\ \beta=\arctan(-\dfrac{z_B}{x_B})\\ \varphi=\text{-}\arccos\dfrac{a_1^2+a_2^2\text{-}(x_B^2+z_B^2+y_B^2)}{2a_1a_2}\end{cases} \tag{10}$$

4.4 Forward kinematics of the lower limb rehabilitation robot

The forward kinematics is solving the position of the end point B_2 based on the known length of each branch. The position vector l_2 which is point B_2 with respect to the fixed arrange frameworks *{A2}:* $l_2=\{l_{2x},l_{2y},l_{2z}\}^T$. The relationship of l_2 and the attitude angle α, β is:

$$\begin{array}{l}l_1^2={a_1}^2-2a_1l_2\sin\beta-2a_1c_1\cos\beta+{l_2}^2+{c_1}^2\\ l_3^2=a2^2+1.9(a_2l_2+a_2d_1)\sin\alpha-2a_2d_2\cos\alpha+{l_2}^2+2l_2d_1+{d_1}^2+{d_2}^2\end{array} \tag{12}$$

According to the cosine theorem we can obtain the relationship of the l_1, l_3 and the attitude angle α, β.

$$\begin{array}{l}\alpha=180(\arcsin(-(q-(t(qt+k(k^2-q^2+t^2)^{(1/2)}))/(k^2+t^2))/k))/pi\\ \beta=180(\arcsin((m-(p(mp+n(-m^2+n^2+p^2)^{(1/2)}))/(n^2+p^2))/n))/pi\end{array} \tag{13}$$

Where:

$$m=-{l_1}^2+{a_1}^2+{l_2}^2+{c_1}^2,\quad n=2a_1l_2,\quad p=2a_1c_2$$

$$q=-{l_3}^2+{a_2}^2+{l_2}^2+2l_2d_1+{d_1}^2+{d_2}^2$$

$$k=1.9a_2(l_2+d_1),\quad t=2a_2d_2$$

Put the equation (13) to the equation (11), we can obtain the position vector l_2 which is the point B_2 relative to the fixed coordinate system *{A2}:* $l_2=\{l_{2x},l_{2y},l_{2z}\}^T$

According to Figure 3, we can obtain the direct kinematics relationship equation. The posture transformation matrix of endpoint C relative to the local coordinate system can be expressed as follows:

$$T=\begin{pmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{14}$$

where :

$$n_x = -c_4(s_1s_3 - c_1c_1c_3) - s_4(c_3s_1 + c_1c_2s_3)$$

$$n_y = c_4(c_1s_3 + c_2c_3s_1) + s_4(c_1c_3 - s_1s_3c_2)$$

$$n_z = -c_{34}s_2;\ o_x = s_4(s_1s_3 + c_2c_3s_1) + s_4(c_1c_3 - c_2s_1s_3)$$

$$o_y = c_4(c_1c_3 - c_2s_1s_3) - s_4(c_1s_3 + c_2c_3s_1);\ o_z = s_{34}s_2$$

$$a_x = c_1s_2;\ a_y = s_1s_2;\ a_z = c_2$$

$$p_x = a_1c_1c_2 - a_3\left(c_4(c_3s_1 + c_2c_1s_3) - s_4(s_1s_3 - c_1c_2c_3) - a_2(s_1s_3 - c_1c_2c_3)_3\right)$$

$$p_y = a_2(c_1s_3 + s_1c_2c_3) + a_3\left(c_4(c_1s_3 - s_1c_2s_3) - s_4(c_1s_3 + s_1c_2c_3) + a_1s_1c_2\right)$$

$$p_z = -s_2(a_1 - a_3s_{34} + a_2c_3)$$

4.5 The Workspace of the Mechanism Leg

The workspace is the one of the most important performance indexes of the series-parallel mechanism. The solution of the workspace of the mechanism leg will provide a basis for the future control and experiment. However, the angle of the motion pairs, the length of the electrical push rod and motion interference between the push rods on the series-parallel mechanism greatly affect the workspace. Then those influence factors will be analyzed below.

Based on the goal of the mechanism design, the end point of the mechanism leg will arrive at the boundary of the workspace when the length of each push rod is at limit value. l_{imin} and l_{imax} represent the minimum value and the maximum value of the length of push rod i . Then the length l_i of the push rod I need be satisfied with the constraint conditions,

$$l_{\min} \le l_i \le l_{\max} \tag{15}$$

where, $262 \le l_1 \le 350.5, 310 \le l_3 \le 510, l_2 = 306$.

In view of the actual the hook hinges and the spherical hinges, we could find that when the lengths of push rods are at limit value, the motion range of the angle of the hinges do not research their limit. So constraint conditions of the hinges will be contained in the constraint conditions of the rush rod lengths. Besides, the branches of the parallel part of the mechanism leg are in two planes perpendicular bending. So there is no interference among the branches.

Based on the workspace characteristic of the mechanism parallel part UPS-UPU-U, the workspace of the mechanism leg is obtained through the software *Matlab* as shown in Figure5. Obviously, the workspace of the mechanism leg is in the three dimensional space. The ranges at X-axis, Y-axis and Z-axis are obtained, where $230 \le x \le 900, -350 \le y \le 800, -580 \le z \le 580$.

From the solution of the workspace, it is large enough to fit with the design of the mechanism leg of the lower limb rehabilitation robot.

5. CONCLUSION

This paper states a spatial four-DOF lower limb rehabilitation robot that is able to be for the rehabilitation training of the patients including lower limb dysfunction. Relative to the now available lower limb rehabilitation robots that most of them can only realize the rehabilitation exercise in the sagittal plane, the proposed lower limb rehabilitation robot with four- DOF spatial motion is more useful. The mechanical plan and its entire structure of the robot are portrayed. The DOF, the forward/backward kinematics and the workspace of the instrument leg are broke down. This examination gives a hypothetical establishment to the control of the restoration robot to meet the solace necessities of the diverse patients (figure 7).

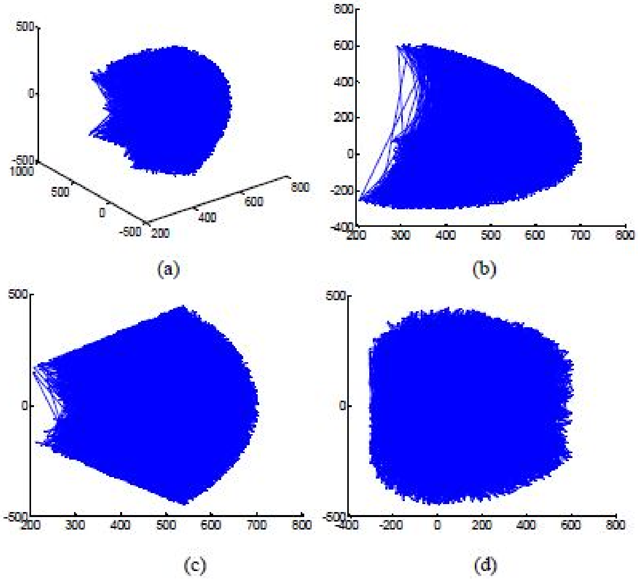


Figure 7: The workspace of the mechanism leg (a)The workspace at the three dimensional space; (b) The workspace in the XY plane; (c) The workspace in the XZ plane; (d) The workspace in the YZ plane.

ACKNOWLEDGEMENTS

"This work implemented with the support of "Joint Laboratory of Intelligent Rehabilitation Robot" collaborative research agreement between Yanshan University, China and Romanian Academy by IMSAR, RO by China Science and Technical Assistance Project for Developing Countries (KY201501009), MEN-UEFISCDI, PN-II-PT-PCCA-2013-4,VIPRO project No.009/2014, Romanian Academy and China National Construction High Level University Government-Sponsored Graduate Student Project (Certificate No. 201608130106)."

REFERENCES

[1] Y.F. Feng, H.B. Wang, T.T. Lu, et al. "Teaching training method of a lower limb rehabilitation robot." Int J Adv Robot Syst, vol. 13, pp. 1-11, February 2016.

https://doi.org/10.5772/62058

[2] F. Zhang, Z.G. Hou, et al. iLeg—A lower limb rehabilitation robot: A proof of concept, IEEE Trans. Human–Mach. Syst., vol 46, pp.761-768, 2016.

[3] X.H. Shi, H.B. Wang, et al. Design and dynamic analysis of an exoskeletal lower limb rehabilitation robot, Journal of Mechanical Engineering, vol 50, pp.41-48, 2014.

https://doi.org/10.3901/JME.2014.03.041

[4] S.Q. Wang, L.T. Wang, et al. Design and control of the MINDWALKER exoskeleton, IEEE T Neur Sys Reh, vol 23, pp.277- 286, 2015.

https://doi.org/10.1109/TNSRE.2014.2365697

[5] G. Chen, C.K. Chan, et al. A review of lower extremity assistive robotic exoskeletons in rehabilitation therapy, Critical Review TM Biomedical Engineering, vol 41, pp. 343–363, 2013.

https://doi.org/10.1615/CritRevBiomedEng.2014010453

[6] G.B. Prange, M.J. Jannink, et al. Influence of gravity compensation on muscle activation patterns during different temporal phases of arm movements of stroke patients, Neurorehab Neural Re, volume 23, number 5, pp.478-485, 2009.

https://doi.org/10.1177/1545968308328720

[7] J. Hidler, W. Wisman, N. Neckel, "Kinematic trajectories while walking within the lokomat robotic gait-orthosis," Clin Biomech, vol. 23, pp. 1251-1259, December 2008.

https://doi.org/10.1016/j.clinbiomech.2008.08.004

[8] X.N. Wang, T. Lu, & S.J. Wang, et al. "A patient-driven control method for lower-limb rehabilitation robot," IEEE ICMA, Harbin, China, pp. 908-913, August 2016.

[9] B.M. Fleerkotte, B. Koopman, J.H. Buurke,& E.H.F.V. Asseldonk, at al., "The effect of impedance-controlled robotic gait training on walking ability and quality in individuals with chronic incomplete spinal cord injury: an explorative study," J Neureong Rehabil, vol. 11, pp.498-500. Mar. 2014.
https://doi.org/10.1186/1743-0003-11-26

[10] J.F. Veneman, R. Kruidhof, E.E.G. Hekman, R. Ekkelenkamp, Van, E.H. Asseldonk. and Van der H. Kooij, Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation. IEEE Trans. Neural Syst. Rehabil. Engng, vol. 15, pp. 379–386, September 2007.

https://doi.org/10.1109/TNSRE.2007.903919

[11] K. J. Chisholm, K. Klumper, A. Mullins, et al.,"A task oriented haptic gait rehabilitation robot," Mechatronics, vol. 24, pp. 1083-1091, December 2014
https://doi.org/10.1016/j.mechatronics.2014.07.001

[12] T. Miyamura, S. Murai, H. Tomisaki, "Therapeutic Exercise Machine LX2", Yaskawa Tech. Rev, vol. 67, pp. 224–228, 2003.

[13] Vladareanu, V; Schiopu, P; Deng, Mingcong; Yu, Hongnian "Intelligent Extended Control of the Walking Robot Motion", 2014 International Conference On Advanced Mechatronic Systems (ICAMECHS), Book Series: International Conference on Advanced Mechatronic Systems, 2014, Pages: 489-495, WOS:000361466100091, ISSN: 2325-0682.

[14] Vladareanu, Victor; Schiopu, Paul; Cang, Shuang; Yu, Hongnian; Deng, Mingcong, "Enhanced Extenics Controller for Real Time Control of Rescue Robot Actuators", 2014 UKACC International Conference On Control (CONTROL) Pages: 725-730 , 2014, WOS:000352626000124, ISBN: 978-1-4799-5011-9

[15] I.L. Koukolová. "Overview of the robotic rehabilitation systems for lower limb rehabilitation," Transfer Inovácií, vol. 2015, pp. 107-111, 2015.

[16] Wang H.B., Zhang D., Lu H., Feng Y.F, Xu P., Mihai R.V., Vladareanu L. "Active training research of a lower limb rehabilitation robot based on constrained trajectory," ICA MechS, Beijing, China, pp. 24-29, August, 22-24, 2015.