Design and Analysis of a Knee Exoskeleton with Self-alignment Capability

Huijuan Lu[1], Tingting Su[2*], Guotao Li[3], Xu Liang[4], Shengda Liu[3], Wendong Xiao[5], Shoulie Xie[6], Jie Zhang[1], and Guangping He[1]

2024 30th International Conference on Mechatronics and Machine Vision in Practice (M2VIP) | 979-8-3503-9191-6/24/$31.00 ©2024 IEEE | DOI: 10.1109/M2VIP62491.2024.10746174

***Abstract*—The knee exoskeleton can assist patients for knee rehabilitation exercises. In this paper, a novel knee exoskeleton with self-alignment capability is proposed. First, the structure of the knee exoskeleton is designed, which has one active and four passive joints. The four passive joints are used to realize the self-alignment function of the knee exoskeleton. Second, the kinematic model is established and analysed. Third, simulations are conducted to validate the rotation ranges of human knee and hip joints. The simulation results demonstrate that the knee exoskeleton can meet the rehabilitation needs of the patients.**

***Index Terms*—knee exoskeleton, structure design, kinematics**

I. Introduction

The knee joint is one of the largest and most complex joints in the human body. It not only participates in daily activities and strenuous sports, but also plays a role in mitigating shocks and keeping the body balanced. During lower limb exercise, the knee joint is susceptible to injury because it is subjected to higher forces compared with other joints. According to literature [1], the knee joint is the joint with the highest morbidity rate in the whole body. The main causes of knee injuries include sports trauma and stroke [2], and knee injuries will seriously affect the patient's activity of daily life and psychological health. The common knee rehabilitation programmes include medication, massage and surgery, etc. Medication and surgery are extremely expensive, and the level of medical expertise varies, resulting in limited rehabilitation effects [3]. Massage usually requires a longer rehabilitation cycle. Meanwhile, the therapist needs to support the patient's weight [4]. The knee exoskeleton can enhance the patient's strength during walking by providing sufficient torque [5]. In addition, it can also provide some relief to the family and community. Therefore, the knee exoskeleton robots is of great significance in assisting the disabled and the elderly, medical rehabilitation and industrial production [6] [7].

Generally the knee exoskeletons can be divided into three categories: rigid exoskeletons, flexible exoskeletons and rigid-flexible coupled exoskeletons. Exoskeletons made of metallic or inelastic materials are rigid exoskeletons. Exoskeletons made of flexible or elastic materials such as textiles and soft polymers are flexible exoskeletons. If the exoskeleton is driven by cables and pulleys, it is rigid-flexible coupled exoskeletons [8].

Rigid exoskeletons can provide adequate strength support to the wearer [9]. It has the advantage of high stability and solidity. Fan et al. proposed a novel knee exoskeleton which consists of a thigh section and a calf section, as shown in Fig. 1(a). It can help patients complete walking rehabilitation and save the patient's lower limb strength [10]. Huang et al. proposed a portable exoskeleton with high stiffness control bandwidth and high torque tracking accuracy, as shown in Fig. 1(b). It can provide a torque of 14 $\mathrm{N\cdot m}$ to the knee joint using a direct drive method [11]. Long et al. proposed a portable and lightweight knee exoskeleton, as shown in Fig. 1(c). It can help the knee of patients achieve 50° [12]. It is worth noting that this type of exoskeleton robots reduce human-robot interaction and safety due to high weight, high inertia, poor control system and unaligned joints [13], and may cause physical discomfort and injury if not adapted to the wearer.

Compared to rigid exoskeletons, flexible exoskeleton reduces constraints on the knee joint and has flexibility. Flexible exoskeletons use flexible materials and have a lighter weight compared to rigid exoskeletons. Cestari et al. designed a knee exoskeleton (ATLAS) that can effectively absorb motion perturbations, as shown in Fig. 1(d). This exoskeleton changes the position of the elastic mechanism, thus changing the overall joint stiffness and making the structure more adaptable [14]. Liu et al. designed a lower limb rehabilitation exoskeleton robot based on flexible transmission, as shown in Fig. 1(e). A flexible axis is added to ensure that the rotational motion and torque are transferred flexibly to any position [15]. Ali et al. proposed a flexible knee exoskeleton robot in which two sets of four SMA springs are arranged at the front and back of the leg to mimic the musculature of the human knee [16]. Wilkening et al. proposed a supple and bendable lower limb exoskeleton robot with multiple degrees of freedom [17], as shown in Fig.

*Corresponding author: Tingting Su. Email: sutingting@bjut.edu.cn.

This work was supported in part by the Talent Fund of Beijing Jiaotong University under Grant KAIXKRC24003532, in part by the National Key R&D Program of China under Grant 2023YFE0202100, in part by the Natural Science Foundation of China under Grants 62103412, 62473365, 62373013, U22A2056, 62103007, and 62473036, in part by the Beijing Natural Science Foundation under Grants L222053, L242101, L232021, and L241058, and in part by the R&D Program of Beijing Municipal Education Commission under Grant KM202210009010 and Grant KM202110009009.

[1]Huijuan Lu, Jie Zhang, and Guangping He are with Department of Mechanical and Electrical Engineering, North China University of Technology, Beijing 100144, China.

[2]Tingting Su is with Faculty of Information Technology, Beijing University of Technology, Beijing 100124, China.

[3]Guotao Li and Shengda Liu are with the State Key Laboratory of Multimodal Artificial Intelligence Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China.

[4]Xu Liang is with School of Automation and Intelligence, Beijing Jiaotong University, Beijing 100044, China.

[5]Wendong Xiao is with School of Automation and Electrical Engineering, University of Science and Technology, Beijing 100083, China.

[6]Shoulie Xie is with Institute for Infocomm Research, A*Star, Singapore.

1(f). Notably, these flexible exoskeletons sacrifice the load capacity of rigid supports and lack the mechanical stops used to constrain the joints working range. As a result, there is a decrease in safety and support strength compared with rigid exoskeletons.

Fig. 1: Various knee exoskeletons. (a) Single-degree-of-freedom knee exoskeleton. (b) Portable knee exoskeleton. (c) Bionic knee exoskeleton. (d) ATLAS knee exoskeleton. (e) Flexible lower limb rehabilitation exoskeleton. (f) BA knee exoskeleton.

Rigid-flexible coupled exoskeletons are a reliatively novel exoskeleton technology in recent years. They have the advantages of high stability, light weight, good human-computer interaction and wearing comfort. Wang et al. proposed a novel rigid-flexible coupled lower limb exoskeleton to provide bi-directional intervention for safe knee motion, which is lightweight at 1.2 kg. It can avoid the rigid centre of rotation that leads to misalignment of the knee joint [18]. Witte et al. proposed a lightweight, torque-controlled rigid-flexible coupled knee exoskeleton with a strong lightweight shell and comfortable leg contact straps. The exoskeleton is structurally compliant in the direction of motion and is instrumented to measure joint angles and apply torque. It weighs only 0.76 kg [19]. Li et al. conducted a series of numerical simulations to compare the rigid-flexible coupled knee exoskeleton model with the rigid knee exoskeleton model under different loads. The simulation results show that the rigid-flexible coupled knee exoskeleton has a better effect on the exoskeleton dynamics under different loads compared with the rigid knee exoskeleton [20].

Knee exoskeletons can assist patients in rehabilitation and prevent patient's muscles from atrophying. However, most existing knee exoskeletons have the following two problems. First, they are relatively complex and not simple enough. Second, they have few passive degrees of freedom, so the self-alignment function of the knee exoskeletons need to be improved. A novel knee exoskeleton with self-alignment capability is proposed in this paper. The structure of this knee exoskeleton is simple. It has one active degree of freedom and four passive degrees of freedom, so this knee exoskeleton can well meet the patient's knee rehabilitation training.

The rest of this paper is organized as follows. The structure and drive mechanism of the knee exoskeleton are described in Section II. The kinematics of the knee exoskeleton is established and analyzed in Section III. The motion range of the knee exoskeleton is calculated and simulations on the rotation ranges of human knee and hip joints are carried out in Section IV. Section V concludes this paper.

II. Structure Design

A. The Knee Exoskeleton Design

A 3D model of the knee exoskeleton is illustrated in Fig. 2. The knee exoskeleton is a PRRRP mechanism. It consists of the thigh exoskeleton mechanism, the attachment mechanism and the calf exoskeleton mechanism. The thigh exoskeleton mechanism is composed of the thigh exoskeleton, elastic straps, and two sliders. The attachment mechanism is made up of a 15cm connecting plate, a 90° ring swivel lever, and the rope pulley. The calf exoskeleton mechanism is formed by the outer straight plate, the 180° ring sheet, the inner straight plate, the calf external rotation plate and a slider. The thigh exoskeleton mechanism and the calf exoskeleton mechanism are connected together by the attachment mechanism.

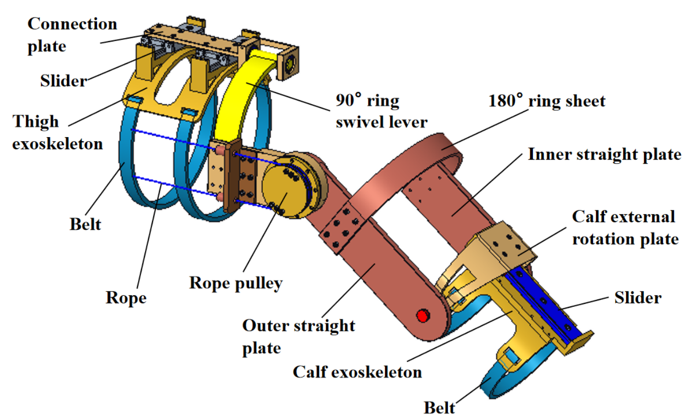


Fig. 2: 3D model of the knee exoskeleton structure.

The thigh exoskeleton is attached to the patient's thigh using elastic straps. There are two sliders on the thigh exoskeleton and the sliders are connected to a 15cm connecting plate. The connecting plate is fixed at a 90° ring swivel lever, which is connected to the rope pulley. The rope pulley is fixed to the outer straight plate, which is linked with the 180° ring sheet. The 180° ring sheet is coupled to the inner straight sheet. The outer and inner straight plates of the knee exoskeleton are fixed as a single unit, and this unit is attached on the external rotation plate of the calf. A slider is mounted underneath the calf external rotation plate.

The thigh exoskeleton and calf exoskeleton are made of carbon fibre using 3D printing technology. They have the advantages of light weight and high strength. The belts are made of polyester fibre. They have the advantages of high elasticity and permeability, multi-layer protection and comfort. The connecting plate, 90° ring swivel lever, rope pulley, 180° ring sheet, inner straight plate, outer straight plate and calf external rotation plate are all made up of Aluminium alloy. They have the advantages of high strength and not easy to deform.

B. Drive Mechanism Design

The drive mechanism is composed of a motor, a planetary reducer, a screwdriver, a slider and two wire ropes. The principle of the drive mechanism is that the motor drives the screwdriver to rotate, and then the screwdriver drives the rope to move. The structure of the drive mechanism is illustrated in Fig. 3. The planetary reducer is connected to the screwdriver through GS-26×21-6-4-5×8 coupling. The screwdriver have a palpitation of 2mm and a length of 120mm, and it can provide a rated dynamic load of 1800N. The drive mechanism can provide the knee joint 50Nm.

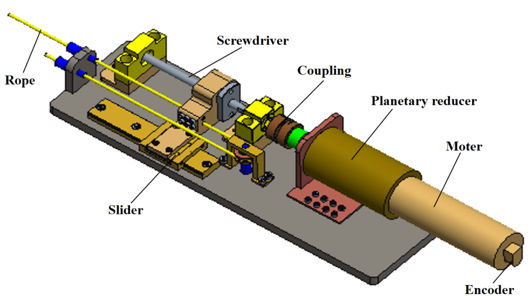


Fig. 3: Drive mechanism of the knee exoskeleton.

C. Movement Patterns

The knee exoskeleton has an active joint q_3 that allows for human knee flexion and extension and four passive joints, namely q_1, q_2, q_4, and q_5 , as shown Fig. 4. The patient's hip internal and external rotation can be achieved by q_2. q_1 and q_2 can improve thigh self-alignment functions of the knee exoskeleton, and q_4 and q_5 can improve calf self-alignment functions of the knee exoskeleton. When the knee exoskeleton drives human knee flexion and extension, q_2 rotates and drives the thigh exoskeleton slider q_1 to slide along the 90° direction of the thigh centre axis. This will complete the self-alignment functions of the knee exoskeleton relative to human thigh movement. Meanwhile, q_4 rotates and drives the calf exoskeleton slider q_5 to slide along the calf centre axis. This will complete the self-alignment functions of the knee exoskeleton relative to human calf movement.

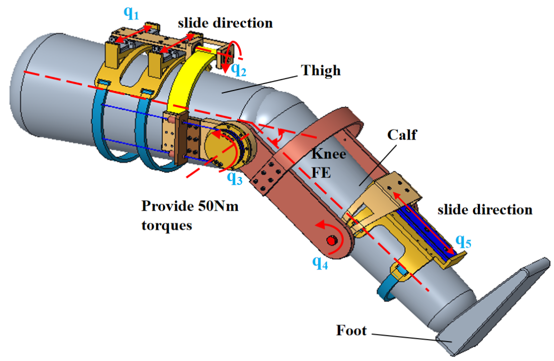


Fig. 4: The knee exoskeleton movement patterns.

III. Kinematic Analysis

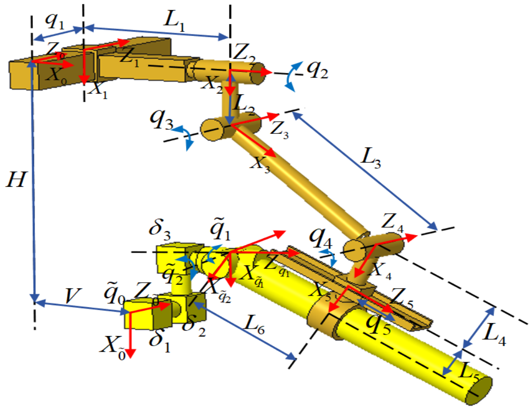
This section first models the kinematics of the knee exoskeleton, and the forward and inverse kinematics are analysed. Second, the relationship between the knee exoskeleton and the human knee joint is calculated. Finally, simulation of the knee and hip joint trajectories is conducted when the human wears the knee exoskeleton.

A. Forward Kinematics

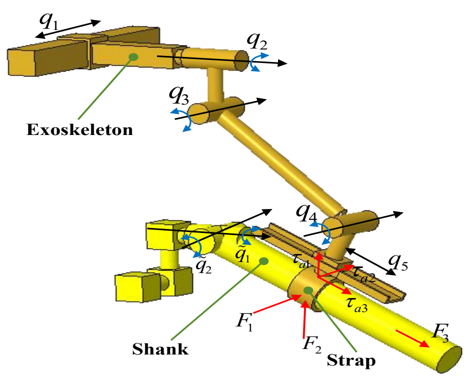
The kinematic model of the exoskeleton is shown in Fig. 5. The knee exoskeleton kinematic chain and the human knee kinematic chain are shown in Fig. 5(a), where V is the x-direction distance variable between the human knee coordinate origin $(X_{\tilde{0}}, Y_{\tilde{0}}, Z_{\tilde{0}})$ and the exoskeleton coordinate origin (X_0, Y_0, Z_0), H is the y-direction distance variable between the human knee coordinate origin $(X_{\tilde{0}}, Y_{\tilde{0}}, Z_{\tilde{0}})$ and the exoskeleton coordinate origin (X_0, Y_0, Z_0). The coordinate vector of the exoskeleton with respect to the human knee is $[V, H, 0]^T$. L_1, L_2, L_3 and L_4 denote the length of the exoskeleton linkage. L_5 denotes the distance from the sliding joint q_5 to the centre axis of the human calf. L_6 denotes the distance from the rotation centre of the human knee joint to the coordinate system $(X_{\tilde{q}_0}, Y_{\tilde{q}_0}, Z_{\tilde{q}_0})$. The knee exoskeleton kinematic chain coordinate system (q_1-q_2-q_3-q_4-q_5) is established based on the modified Denavit-Hartenberg (D-H) modelling algorithm. The Modified D-H parameters of the knee exoskeleton are shown in Table I. The human joint kinematic chain coordinate system ($\tilde{q}_0$-$\tilde{q}_1$-$\tilde{q}_2$) is established based on the chi-square transformation matrix method. The Modified D-H parameters of the human knee joint are shown in Table II.

TABLE I: Modified D-H parameters of the knee exoskeleton

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	q_1	90°
2	90°	0	L_1	q_2
3	−90°	L_2	0	q_3
4	0	L_3	0	q_4
5	90°	L_4	q_5	0



(a)



(b)

Fig. 5: Kinematic model. (a) The knee exoskeleton kinematic chain and the human knee kinematic chain. (b) Interaction force analysis.

TABLE II: Modified D-H parameters of the human knee joint

i	α_{i-1}	a_{i-1}	d_i	θ_i
$\tilde{0}$	0	0	0	90°
$\tilde{1}$	90°	0	0	$\tilde{q}_1$
$\tilde{2}$	−90°	0	0	$\tilde{q}_2$
$\tilde{3}(5)$	90°	$-L_5$	L_6	0

Based on the D-H parameters of the knee exoskeleton, the transformation matrices for each joint in the exoskeleton can be obtained as ${}^0_1\mathbf{T}$, ${}^1_2\mathbf{T}$, ${}^2_3\mathbf{T}$, ${}^3_4\mathbf{T}$, and ${}^4_5\mathbf{T}$. The end position and posture of the knee exoskeleton can be represented

$$ {}^0_5\mathbf{T}^E(\mathbf{q}) = {}^0_1\mathbf{T}{}^1_2\mathbf{T}{}^2_3\mathbf{T}{}^3_4\mathbf{T}{}^4_5\mathbf{T} \tag{1} $$

where ${}^{i-1}_{i}\mathbf{T}$ is the chi-square transformation matrix corresponding to the knee exoskeleton. $q = [q_1, q_2, q_3, q_4, q_5]^T$ is the joint rotation angle of the knee exoskeleton.

Based on the D-H parameters of the human knee joint, the transformation matrices of the individual joints in the human body can be obtained as ${}^0_{\tilde{0}}\bar{\mathbf{T}}$, ${}^{\tilde{0}}_{\tilde{1}}\mathbf{T}$, ${}^{\tilde{1}}_{\tilde{2}}\mathbf{T}$, and ${}^{\tilde{2}}_{\tilde{3}(5)}\mathbf{T}$. The end position and posture of the human knee joint can be represented

$$ {}^0_5\mathbf{T}^K(\tilde{\mathbf{q}}) = {}^0_{\tilde{0}}\bar{\mathbf{T}}{}^{\tilde{0}}_{\tilde{1}}\mathbf{T}{}^{\tilde{1}}_{\tilde{2}}\mathbf{T}{}^{\tilde{2}}_{\tilde{3}(5)}\mathbf{T} \tag{2} $$

where ${}^0_{\tilde{0}}\bar{\mathbf{T}} = \mathbf{Trans}(V + \delta_3, H - \delta_2, \delta_1){}^0_{\tilde{0}}\mathbf{T}$. $q = [q_1, q_2, q_3, q_4, q_5]^T$ is the rotation angle of the human joint.

Based on the end position and attitude of the knee exoskeleton and the human knee, the kinematic equations of the spatial closed-loop mechanism can be established

$$ {}^0_5\mathbf{T}^E(\mathbf{q}) = {}^0_5\mathbf{T}^K(\tilde{\mathbf{q}}) \tag{3} $$

Eq. (3) can be transformed into

$$ \begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \delta_1 \\ \delta_2 \\ \delta_3 \end{pmatrix} = \begin{pmatrix} q_2 \\ q_3 + q_4 \\ q_1 + s_2((q_5 - L_6)s_{34} + (L_4 + L_5)c_{34} + L_2 + L_3c_3) \\ H - c_2((q_5 - L_6)s_{34} + (L_4 + L_5)c_{34} + L_2 + L_3c_3) \\ L_1 - V + (q_5 - L_6)c_{34} - (L_4 + L_5)s_{34} - L_3s_3 \end{pmatrix} \tag{4} $$

where sin is denoted as s, and cos is denoted as c.

It can be obtained according to Eq. (4)

$$ \tilde{q}_2 = q_3 + q_4 = 2\arctan\frac{B + \sqrt{A^2 + B^2 - C^2}}{A + C} \tag{5} $$

where $A = H - L_2c_2 - L_3c_2c_3$, $B = (L_1 - V - L_3s_3)c_2$, $C = (L_4 + L_5)c_2 + \delta_2c_{34} + \delta_3c_2s_{34}$.

B. Inverse Kinematics

Similar to the forward kinematics, the inverse kinematics can be obtained

$$ A'\cos q_3 + B'\sin q_3 = C' \tag{6} $$

$$ q_3 = 2\arctan\frac{B' - \sqrt{B'^2 - C'^2 + A'^2}}{C' + A'} \tag{7} $$

where $A' = L_3c_{\tilde{q}_1}c_{\tilde{q}_2}$, $B' = L_3c_{\tilde{q}_1}s_{\tilde{q}_2}$, $C' = (L_1 - V)c_{\tilde{q}_1}s_{\tilde{q}_2} - (L_4 + L_5)c_{\tilde{q}_1} + Hc_{\tilde{q}_2} - \delta_2c_{\tilde{q}_2} - \delta_3c_{\tilde{q}_1}s_{\tilde{q}_2}$. From the third and fourth lines of Eq. (4), we have

$$ q_1 = (H - \delta_2)\,\mathrm{tanq_2} + \delta_1 \tag{8} $$

Define the inverse kinematics of the knee as

$$ \tilde{q} = X(q_a, \delta) \tag{9} $$

where $\mathbf{q}_a = q_3$.

According to Eq. (7), $\mathbf{q}_a$ can be described as a function of $\tilde{q}_2$.

C. Analysis of Human Knee Joint Forces

As shown in Fig. 5(b), the knee exoskeleton, human knee and calf form a spatially closed-loop mechanism. F_1 and F_2 denote the forces acting on human calf by the knee exoskeleton. F_3 denotes a constraining force along the axis of human's calf. τ_1, τ_2 and τ_3 denote the constraining torque of the knee exoskeleton acting on human calf. F_1 and F_2 can be transformed into forces that are useful for human knee. F_3 may cause injury to human calf. Therefore, F_3 must be reduced or eliminated for safety. In this paper, F_3 can be eliminated by sliding the passive joint q_5. In terms of the knee exoskeleton work efficiency, when F_1, F_2 and F_3 are smaller, the knee exoskeleton will have higher work efficiency.

It is assumed that the change in position of human knee joint is small and $\dot{\delta} = 0$. Then, we can get

$$\dot{\tilde{q}} = J\left(q_a\right)\dot{q}_a \tag{10}$$

where $\dot{\tilde{q}}$ denotes the velocity vector of the human knee joint, $\dot{\mathrm{q}}_a$ denotes the velocity vector of the knee exoskeleton. $J\left(\mathrm{q}_a\right)$ denotes the Jacobi matrix. According to the principle of virtual work, we have

$$\tau_{q_a} = J^T\left(q_a\right)\tau_{\tilde{q}} \tag{11}$$

where τ_{q_a}=τ_{q_3} denotes the torque vector of the knee exoskeleton, and $\mathrm{J}^{\mathrm{T}}(\mathrm{q}_a)$=$a_{11}$. The torque on human knee joint can be expressed as $\tau_{\tilde{q}} = \tau_{\tilde{q}_2}$. According to Eq. (11), we have

$$\tau_{q_3} = a_{11}\tau_{\tilde{q}_2} \tag{12}$$

Eq. (12) is the torque relationship between the knee exoskeleton and human calf.

IV. Calculation of Human Joint Motion Range

A. Calculation of Human Knee Joint Motion Range

The relationship between the knee exoskeleton joint q_3 and human knee joint $\tilde{q}_2$ can be obtained from Eq. (5). The motion range of q_3 is designed to -90°-0°. The size parameters of the knee exoskeleton are set to $L_1 = 96mm$, $L_2 = 100mm$, $L_3 = 200mm$, $L_4 = -68mm$, $L_5 = 68mm$, $L_6 = 250mm$, $V = 190mm$, $H = 95mm$. According to Eq. (5), the motion range of $\tilde{q}_2$ can be calculated. The motion relationship between $\tilde{q}_2$ and q_3 is shown in Fig. 6(a). When $\tilde{q}_2$ equals to 0°, it denotes that human knee is in an extension state. When $\tilde{q}_2$ equals to 120°, it denotes that human knee is in a flexion state. The 0°-120° rotation range of $\tilde{q}_2$ conforms to the motion range of human knee. Therefore, the knee exoskeleton can assist the patient for knee flexion and extension.

B. Calculation of Human Hip Joint Motion Range

The relationship between the knee exoskeleton joint q_2 and human hip joint $\tilde{q}_1$ can be obtained as

$$\tilde{q}_1 = q_2 \tag{13}$$

The motion range of joint q_2 is designed to -10°-10°. The structural parameters of the exoskeleton remain unchanged.

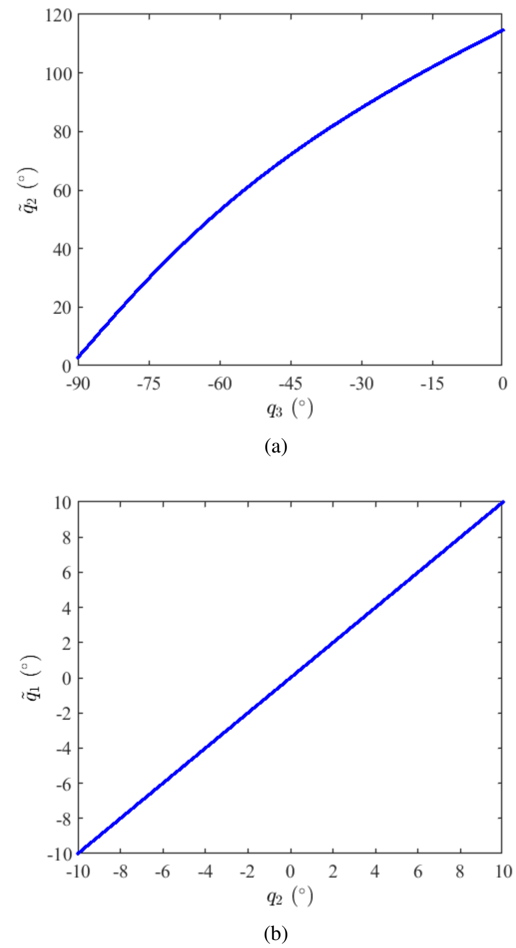


Fig. 6: Motion relationships between joints. (a) Relationship between the motion of $\tilde{q}_2$ and q_3. (b) Relationship between the motion of $\tilde{q}_1$ and q_2.

According to Eq. (13), the motion range of $\tilde{q}_1$ can be calculated. The motion relationship between $\tilde{q}_1$ and q_2 is shown in Fig. 6(b). When $\tilde{q}_1$ equals to -10°, it denotes that human hip is in an internal state. When $\tilde{q}_1$ equals to 10°, it denotes that human hip is in an external state. The -10°-10° rotation range of human hip internal and external can be allowed by the knee exoskeleton. In addition, the self-alignment capability of the knee exoskeleton can be realised by human hip internal and external rotation.

V. Conclusion

In this paper, a knee exoskeleton with self-alignment capability is proposed. It has one active joint and four passive joints. The patient's knee flexion and extension motion can be accomplished through the active joint of the knee exoskeleton. The self-alignment capability of the knee exoskeleton can be realised by the four passive joints. By analysing the forward kinematics of the knee exoskeleton, the relationship between the human knee joint $\tilde{q}_2$ and the knee exoskeleton joint q_3 can be obtained. The simulation results show that the motion range of human knee flexion and extension is 0°-120°. By analysing the inverse kinematics of the knee exoskeleton, the relationship between the human hip joint $\tilde{q}_1$ and the knee exoskeleton joint q_2 can be obtained. The simulation results show that the motion range of human hip joint internal and external is -10°-10°. Automatic alignment of the rope pulley axis of the knee exoskeleton to the axis of human knee joint can be achieved by internal and external rotation of the human hip joint. In summary, the knee exoskeleton can help patients with knee rehabilitation. The effect of movement ranges of sliders on the self-alignment performance of the knee exoskeleton will be verified in the future. Furthermore, the active freedoms of the knee exoskeleton will be increased to achieve more rehabilitation training modes of the knee exoskeletons.

REFERENCES

[1] L. Sharma, "Osteoarthritis of the knee," *New England Journal of Medicine*, vol. 384, no. 1, pp. 51–59, 2021.

[2] M. De Carlo and B. Armstrong, "Rehabilitation of the knee following sports injury," *Clinics in Sports Medicine*, vol. 29, no. 1, pp. 81–106, 2010.

[3] B. Zhong, K. Guo, H. Yu, and M. Zhang, "Toward gait symmetry enhancement via a cable-driven exoskeleton powered by series elastic actuators," *IEEE robotics and automation letters*, vol. 7, no. 2, pp. 786–793, 2021.

[4] X. Liang, Y. Yan, W. Wang, T. Su, G. He, G. Li, and Z.-G. Hou, "Adaptive human–robot interaction torque estimation with high accuracy and strong tracking ability for a lower limb rehabilitation robot," *IEEE/ASME Transactions on Mechatronics*, 2024, doi: 10.1109/TMECH.2024.3394491.

[5] M. Zhang, C. Wang, C. Zhang, P. Li, and L. Liu, "A unified switching control framework for continuous robot-assisted training," *IEEE/ASME Transactions on Mechatronics*, vol. 29, no. 4, pp. 2743–2755, 2024.

[6] J. Wang, W. Chen, X. Xiao, Y. Xu, C. Li, X. Jia, and M. Q.-H. Meng, "A survey of the development of biomimetic intelligence and robotics," *Biomimetic Intelligence and Robotics*, vol. 1, no. 1, p. 100001, 2021.

[7] X. Liang, G. He, T. Su, W. Wang, C. Huang, Q. Zhao, and Z.-G. Hou, "Finite-time observer-based variable impedance control of cable-driven continuum manipulators," *IEEE Transactions on Human-Machine Systems*, vol. 52, no. 1, pp. 26–40, 2021.

[8] H. Güçlü and A. Cora, "A survey on wearable hand robotics design for assistive, rehabilitative, and haptic applications," *International Journal of Intelligent Robotics and Applications*, vol. 7, no. 2, pp. 227–252, 2023.

[9] X. Wang, H. Yu, S. Kold, O. Rahbek, and S. Bai, "Wearable sensors for activity monitoring and motion control: A review," *Biomimetic Intelligence and Robotics*, vol. 3, no. 1, p. 100089, 2023.

[10] L. Fan, L. Yan, J. Xiao, and F. Wang, "Dynamics analysis and simulation verification of a novel knee joint exoskeleton," *Journal of Vibroengineering*, vol. 19, no. 4, pp. 3008–3018, 2017.

[11] T.-H. Huang, S. Zhang, S. Yu, M. K. MacLean, J. Zhu, A. Di Lallo, C. Jiao, T. C. Bulea, M. Zheng, and H. Su, "Modeling and stiffness-based continuous torque control of lightweight quasi-direct-drive knee exoskeletons for versatile walking assistance," *IEEE Transactions on Robotics*, vol. 38, no. 3, pp. 1442–1459, 2022.

[12] Y. Long and Y. Peng, "Design and control of a quasi-direct drive actuated knee exoskeleton," *Journal of Bionic Engineering*, vol. 19, no. 3, pp. 678–687, 2022.

[13] P. Li, L. Wang, G. Zhu, and M. Zhang, "Predictive active disturbance rejection control for servo systems with communication delays via sliding mode approach," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 12, pp. 12679–12688, 2020.

[14] M. Cestari, D. Sanz-Merodio, J. C. Arevalo, and E. Garcia, "An adjustable compliant joint for lower-limb exoskeletons," *IEEE/ASME Transactions On Mechatronics*, vol. 20, no. 2, pp. 889–898, 2014.

[15] K. Liu, L. Li, W. Li, J. Gu, and Z. Sun, "Compliant control of lower limb rehabilitation exoskeleton robot based on flexible transmission," *Journal of Bionic Engineering*, vol. 20, no. 3, pp. 1021–1035, 2023.

[16] H. F. Ali and Y. Kim, "Design procedure and control of a small-scale knee exoskeleton using shape memory alloy springs," *Microsystem Technologies*, vol. 29, no. 8, pp. 1225–1234, 2023.

[17] A. Wilkening, S. Hacker, H. Stöppler, L. Dürselen, and O. Ivlev, "Experimental and simulation-based investigation of polycentric motion of an inherent compliant pneumatic bending actuator with skewed rotary elastic chambers," *Robotics*, vol. 6, no. 1, pp. 2–12, 2017.

[18] Z. Wang, Z. Zhou, L. Ruan, X. Duan, and Q. Wang, "Mechatronic design and control of a rigid-soft hybrid knee exoskeleton for gait intervention," *IEEE/ASME Transactions on Mechatronics*, vol. 28, no. 5, pp. 2553–2564, 2023.

[19] K. A. Witte, A. M. Fatschel, and S. H. Collins, "Design of a lightweight, tethered, torque-controlled knee exoskeleton," in *2017 International Conference on Rehabilitation Robotics (ICORR)*, pp. 1646–1653, IEEE, 2017.

[20] Z. Li, X. Guan, H. Li, Y. Liu, X. Mao, X. Li, and C. Xu, "Numerical study on dynamics of exoskeleton with rigid-flexible coupling knees based on sagittal gait plan," *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, vol. 13, no. 3, pp. 49–62, 2019.