Performance analysis of a cable-driven ankle assisting device

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Abstract. The paper presents a cable-driven parallel manipulator as a device for the motion assistance of the human ankle. The proposed design solution is discussed with design and operation requirements as from consideration of biomechanics and human-machine interaction. A performance evaluation is carried out to check the feasibility of the proposed design and to characterize its operation efficiency. Simulation results are discussed to give numerical estimation for a future prototype construction.

Keywords: Cable Parallel Manipulators, Motion Assistance, Design, Ankle Biomechanics, Simulation

1 Introduction

The ankle joint of the human body is susceptible to musculoskeletal and neurological injures. For muscular rehabilitation, patients perform training exercises with the supervision of a therapist, which are a time-consuming and repetitive process that requires constant attention from both patient and therapist. Moreover, training sessions are short, while a continuous muscular activity of the injured joint would shorten rehabilitation time and improve joint motion recovery. Robotic system such as exoskeletons can make the process less intensive for the therapist and increase the duration and frequency of training sessions, so that rehabilitation can be provided in a better and faster way.

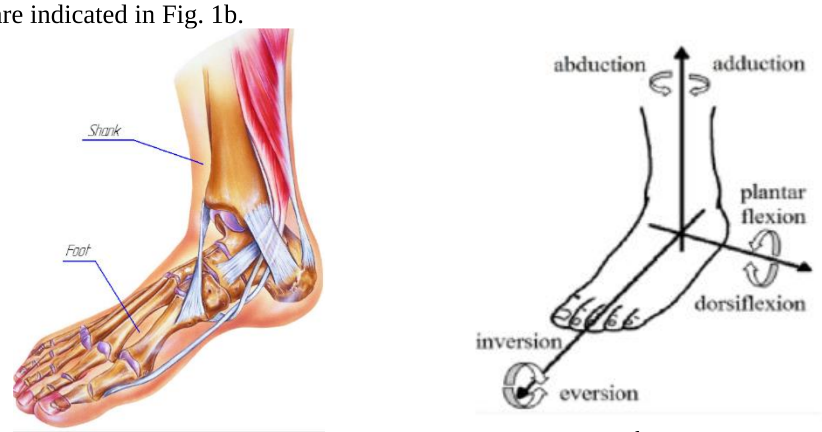
According to this idea, many concepts of parallel rehabilitation robots have been presented in literature [1]. In [2], a parallel-platform-based robot is presented. This robot provides 3 rotational degrees of freedom (DOF) for the ankle with a good interaction between the robot, patient, and therapist. In [3] a wearable robot is proposed for post-stroke lower limb rehabilitation, but its usefulness is limited by large volume, heavy mass, and complicated structure. In [4], another wearable rehabilitation mechanism with 6 DOF is presented and evaluated, but it is heavy and difficult to move. Conversely, the portable robot in [5], based on spherical mechanism, provides 3 DOF and it can be used at home and fitness for ankle muscle relaxation.

A device which is based on a cable-driven manipulator, already applied to fields such as space, biomechanics, transporting, safety systems, and rescue operations [6], could solve the problems of safety [7], non-portability, complicated actuation, device encumbrance and weight, as reported in [8]. Thus, a cable-driven parallel manipulator can apply the necessary load to the foot by applying a constant tension to the cables, in order to rotate the ankle joint enough to activate muscles, but in a controlled motion to avoid further pain or injury.

In this paper, the novel device first proposed in [8] is analyzed and characterized with numerical simulation, in order to evaluate both its kinematic and static behavior.

2 Requirements for ankle motion assistance

The ankle anatomy is shown in Fig. 1a, whereas its characteristic motion parameters are indicated in Fig. 1b.



a. b.

Fig. 1 The foot-ankle system: a. Anatomy; b. A scheme of ankle motion.

As shown in Fig. 1b, the ankle joint allows different types of independent motions such as inversion-eversion, abduction-adduction, and plantarflexion-dorsiflexion around three perpendicular axes. For rehabilitation, operating these independent rotations is usually enough, without considering the limited (negligible) translations allowed by the ankle joint. An ankle rehabilitation device should provide angles within motion range limits, in order to avoid pain or injury for the patient and train effectively after being weakened by injury or inactivity. The limitations for human motion are assumed as from -8 deg to 8 deg for inversion-eversion and from -32 deg to 40 deg for plantarflexion-dorsiflexion [9]. Additional requirements for an ankle rehabilitation device also include parameters such as portability, weight, comfort, size, and user-friendliness, as explained in [10]. Finally, the user interface should provide the option to change the maximum loading condition of the ankle.

3 The proposed design

The proposed device, introduced in [8], can be represented by two platforms which are connected by four cables, as shown in Fig. 2. The upper platform, representing the shank, is fixed, and the lower platform, representing the foot, moves within the motion range by variating the lengths of four actuation cables. The kinematic behavior of the ankle is considered as a spherical joint, as proposed in [8].

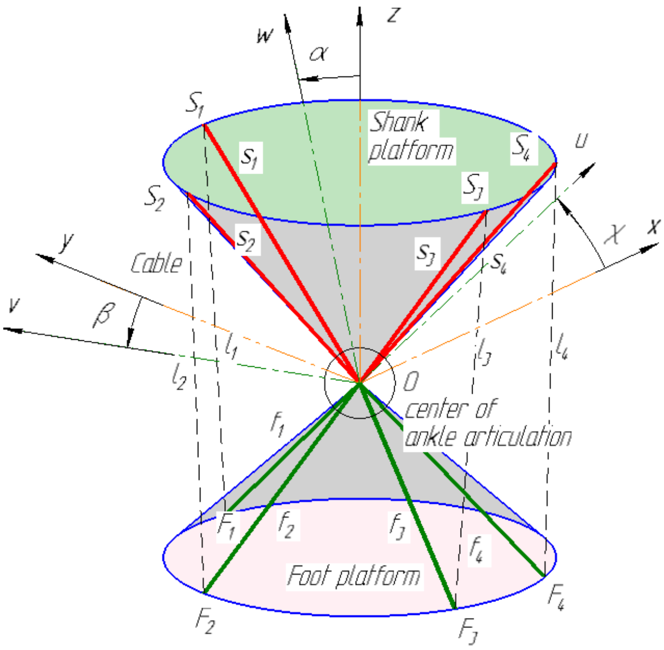


Fig. 2. A kinematic scheme of ankle with design parameters

The following hypotheses are assumed:

- All the cables are always kept in tension during a controlled motion,
- The attachment point of each cable is assumed as a spherical joint,
- The varying length of the cable can be modeled as an actuated cylindrical joint with a negligible axial deformation.

A CAD solution of the mechanical device is presented on the Fig. 3a. Servomotors actuate the lengths of cables l_1, l_2, l_3 and l_4 to provide a proper rotation of the foot platform.

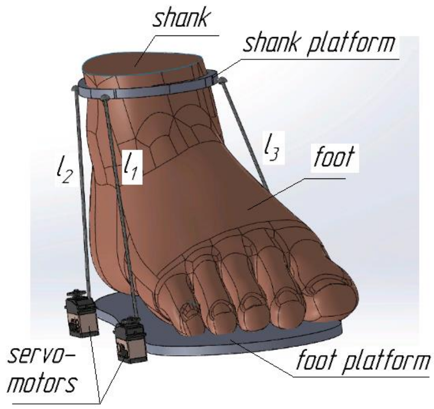


Fig. 3. A CAD solution of the mechanical design

In Fig. 2, the reference frame of the shank platform is O_{xyz} and the reference frame of foot is O_{uyw}. The i[th] cable's upper extremity is attached to point S_i of the shank platform and its lower point is attached by point F_i of the foot platform. A general relative motion of the ankle joint can be described by three consecutive rotations around three axes as in Fig. 1b. Thus, the orientation of the foot platform can be expressed as $^{SF}\boldsymbol{R} = \boldsymbol{R_z(\alpha)R_y(\beta)R_x(\gamma)}$.

The position of the i[th] cable attachment is $^s\boldsymbol{s}_i = (s_{ix}\ s_{iy}\ s_{iz})^T$ for the shank platform and $^f\boldsymbol{f}_i = (f_{xi}\ f_{yi}\ f_{zi})^T$ for the foot platform. The ankle pose can be described as $\boldsymbol{x} = (\alpha\ \beta\ \gamma)^T$, where α, β and γ are the rotations around z-, y-, x- axes, as it was previously defined. The actuation can be expressed by $\boldsymbol{q} = (l_1\ l_2\ l_3\ l_4)^T$, where l_i is the distance between points S_i and F_i of each cable, computed as magnitude of vectors l_i in Fig. 2. Vectoral loop-closure equations for each cable can be expressed as

$$\boldsymbol{OS_i} + \boldsymbol{S_i F_i} + \boldsymbol{F_i O} = \boldsymbol{0} \quad (1)$$

The cable vector is computed from (1) as:

$$^S\boldsymbol{l_i} = {}^{SF}\boldsymbol{R}\,{}^F\boldsymbol{f_i} - {}^S\boldsymbol{s_i} \quad (2)$$

Then, by computing the scalar product of each side by itself, the length of each cable can be expressed as

$$l_i = \sqrt{{}^S\boldsymbol{s}_i^T\,{}^S\boldsymbol{s_i} + {}^F\boldsymbol{f}_i^T\,{}^F\boldsymbol{f_i} - 2\,{}^S\boldsymbol{s}_i^T\,{}^{SF}\boldsymbol{R}\,{}^F\boldsymbol{f_i}} \quad (3)$$

The device with a controlled smooth motion should provide no stress, pain, or damage to the patient. Because of the negligible moving mass and the slow speed, dynamics and inertial effects can be neglected so that performance analysis can be modelled by a static model where the weight of the foot and the platform are applied to the ankle joint itself. When external forces are considered, the actuation should balance them to maintain equilibrium. To this aim, reaction force F_A and reaction moment M_A of a reference point which is considered as a center of ankle actuation can be used to maintain to keep the whole system in static equilibrium. F_W and M_W are the external force and torque, in this case representing the foot's own weight. A force diagram of the moving platform is shown in Fig. 4.

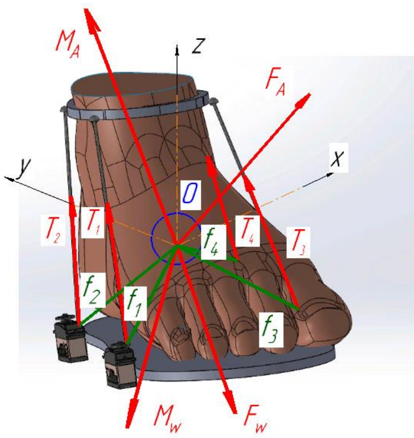


Fig. 4. A model for static equilibrium of the proposed solution.

Force equilibrium can be expressed as

$$\sum_{i=1}^{4} \boldsymbol{T_i} + \boldsymbol{F_a} + \boldsymbol{F_w} = 0 \tag{4}$$

Moment equilibrium can be expressed as

$$\sum_{i=1}^{4} \boldsymbol{f_i} \times \boldsymbol{T_i} + \boldsymbol{M_a} + \boldsymbol{M_w} = 0 \tag{5}$$

By using cable unit vector $\mathbf{u}_i$ the tension of cable can be expressed as $\boldsymbol{T}_i$=-$\boldsymbol{T_i u_i}$. The actuation vector $\mathbf{T}_i$ with components (T_1, T_2, T_3, T_4) can be used to rewrite Eqs (4) and (5) as

$$\boldsymbol{U}^{\mathrm{T}} \cdot \boldsymbol{T} - \boldsymbol{F_A} = \boldsymbol{F_W} \tag{6}$$

$$\boldsymbol{A}^{\mathrm{T}} \cdot \boldsymbol{T} - \boldsymbol{M_A} = \boldsymbol{M_W} \tag{7}$$

where $\boldsymbol{U}^{\mathrm{T}} = [\boldsymbol{u_1} \quad \boldsymbol{u_2} \quad \boldsymbol{u_3} \quad \boldsymbol{u_4}]$ and $\boldsymbol{A}^{\mathrm{T}} = [\boldsymbol{f_1} \times \boldsymbol{u_1} \quad \cdots \quad \boldsymbol{f_4} \times \boldsymbol{u_4}]$.

Reaction moment $\boldsymbol{M}_A$ is a null vector when the ankle joint is modelled as a spherical joint, and the full equilibrium can be formulated as

$$\begin{bmatrix} \boldsymbol{U}^{\mathrm{T}} & -\mathbf{I_3} \\ \boldsymbol{A}^{\mathrm{T}} & \mathbf{0_3} \end{bmatrix} \begin{pmatrix} \boldsymbol{T} \\ \boldsymbol{F_A} \end{pmatrix} = \begin{pmatrix} \boldsymbol{F_W} \\ \boldsymbol{M_W} \end{pmatrix} \tag{8}$$

to determine the actuation vector with its components when an input motion is given.

4 Results for performance analysis

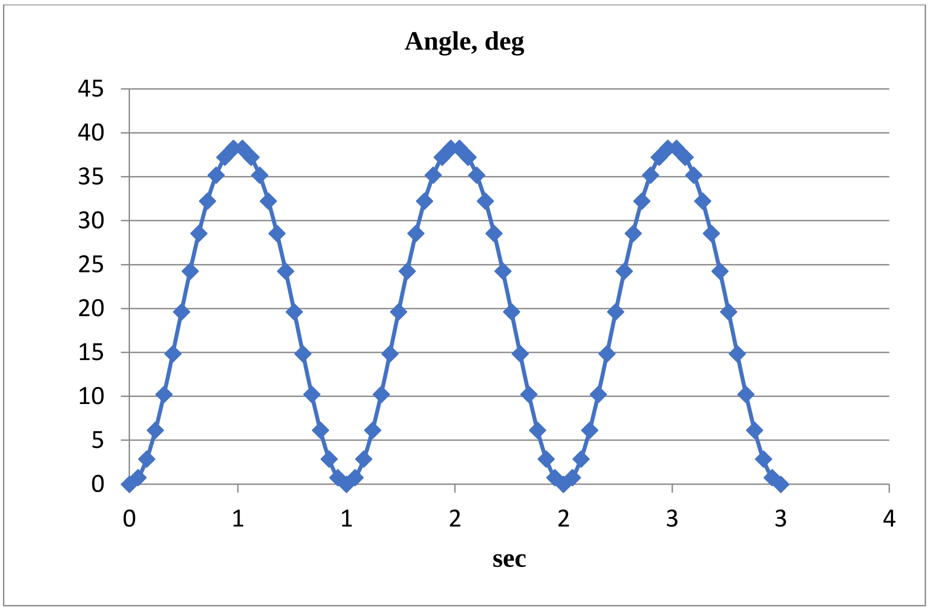
In order to evaluate the performance of the proposed mechanism, a motion analysis has been performed with a multibody simulation tool on Solidworks. This motion analysis studies typical rehabilitation motion, which are characterized by the angular motion laws in Fig. 5. The results for reaction force of the reference point of the mechanism (on the ankle joint) are reported in Fig. 6, while Fig. 7 indicates the change in cable lengths. The simulation results have been computed by assuming an appropriate load onto cable as tension to obtain the desired motion. The foot mass has been estimated as 0,860 kg for an exercise of the ankle in the air. The criteria for defining the tension force onto cables required foot reaction force to be smaller than the maximum load sustainable by an injured foot, which is about 50 N [11].

The performance has shown that, with these input parameters, the reaction force of the reference joint (ankle) for the abduction-adduction movement quickly reaches 50 N, which is the upper limit for the load on an injured human ankle. Thus, for performing at the full exercising angle, an increase of cable tension would be required, but it cannot be provided as it would result into a load higher than the maximum one that injured human ankle could bear [11]. Within a safe limited abduction-adduction motion, the maximum tension observed in the actuation cables is 16 N.

Conversely, for the reported dorsiflexion-plantarflexion exercise, the maximum value of the reaction force is 10 N, which is acceptable for an injured ankle. The maximum applied input force on the cable is 18 N. In the reported inversion-eversion movement the maximum value of the ankle joint reaction force is 5 N, and the applied input force on the cables to provide the rehabilitation motion is 5 N.

As shown in the results in Fig. 8, both these motion exercises result in a smooth distribution of the ankle reaction force in time, without sudden changes or discontinuities. This uniform rate is desirable in a rehabilitation system, as the lack of impulsive loads significantly reduces the chance of injuring the patient during exercising. Furthermore, this feature also reflects on control performance, as reported in Fig. 10, since the cable velocity and acceleration are limited throughout the entire operation and does not demand power peaks or high performance from the actuators. This enables the use of conventional servomotors to drive the system, reducing cost and improving the accessibility of the device to general patients.

Overall, the reported result prove the feasibility of the proposed cable-driven assistive device, by demonstrating its capability to guide a patient through most of the critical exercises for ankle rehabilitation. Furthermore, the numerical characterization can be used to define design requirement for a future prototype.



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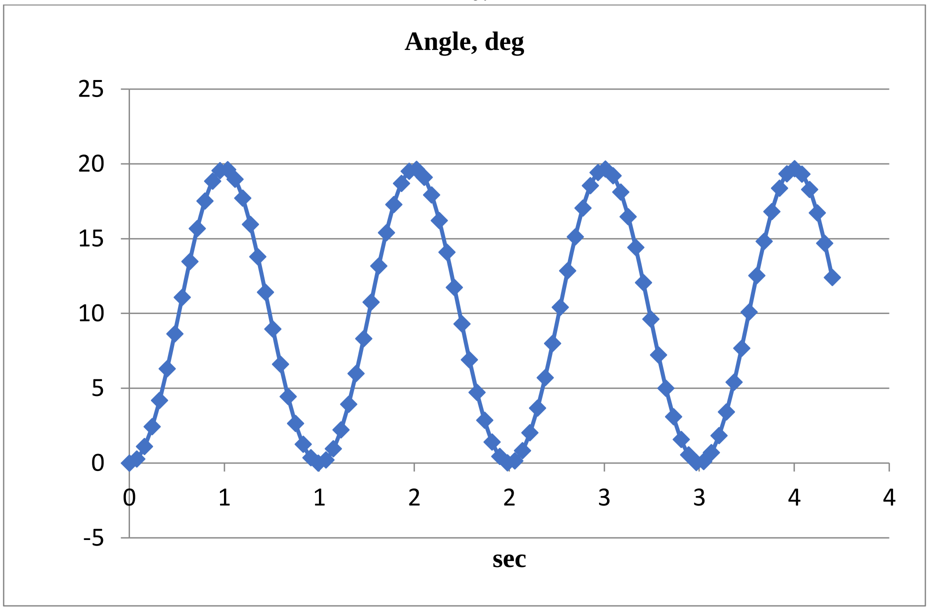
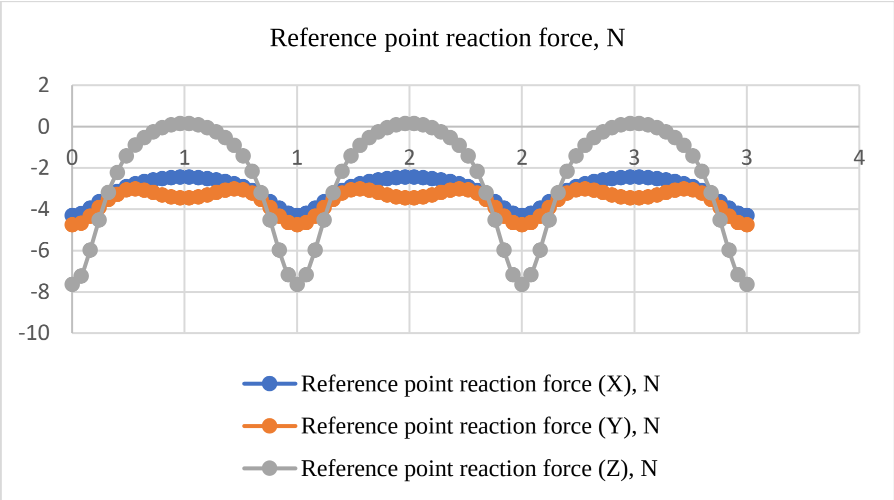


b.

Fig. 5. Evaluated change of angle for an harmonical load: a. Dorsiflexion/plantarflexion; b. Inversion/eversion.



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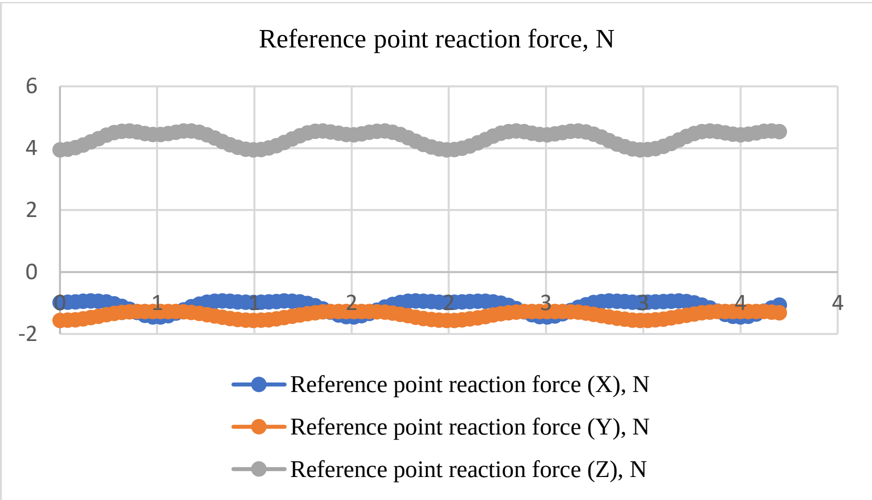
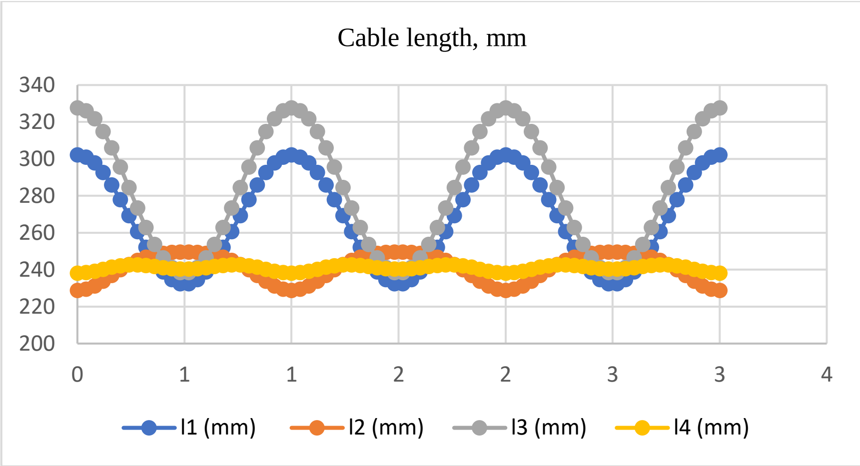
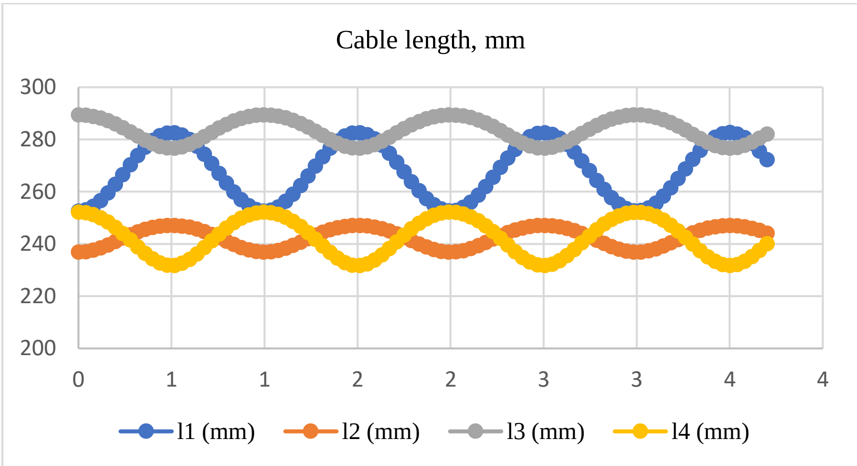


b.

Fig. 8. Reaction force of the reference point for harmonical load: a. Dorsiflexion/plantarflexion; b. Inversion/eversion.



a.



b.

Fig. 10. Cable lengths: a. Dorsiflexion/plantarflexion; b. Inversion/eversion/

5 Conclusions

In this paper, a cable-driven parallel manipulator is proposed as a device for motion assistance of human ankle. The design solution is discussed with design and motion requirements that are derived by considering biomechanics and human-machine interaction. A performance evaluation is carried out to check the feasibility of the proposed design and to characterize its operation efficiency. Simulation results were obtained as a numerical estimation of device performance for a future prototype construction.

References

1. Dong, M., Zhou, Y., Li, J., Rong, X., Fan, W., Zhou, X., & Kong, Y. (2021). State of the art in parallel ankle rehabilitation robot: a systematic review. Journal of NeuroEngineering and Rehabilitation, 18(1), 1-15. https://doi.org/10.1186/s12984-021-00845-z
2. Zhang, L., Li, J., Dong, M., Fang, B., Cui, Y., Zuo, S., & Zhang, K. (2019). Design and workspace analysis of a parallel ankle rehabilitation robot (PARR). Journal of healthcare engineering, 2019. https://doi.org/10.1155/2019/4164790
3. Zhang, X., Yue, Z., & Wang, J. (2017). Robotics in lower-limb rehabilitation after stroke. Behavioural neurology, 2017. https://doi.org/10.1155/2017/3731802
4. Zuo, S., Li, J., Dong, M., Zhou, X., Fan, W. and Kong, Y., 2020. Design and performance evaluation of a novel wearable parallel mechanism for ankle rehabilitation. Frontiers in neurorobotics, 14, p.9.
5. Du, Y., Li, R., Li, D., & Bai, S. (2017). An ankle rehabilitation robot based on 3-RRS spherical parallel mechanism. Advances in Mechanical Engineering, 9(8), 1687814017718112. https://doi.org/10.1177/1687814017718112
6. Qian, S., Zi, B., Shang, W. W., & Xu, Q. S. (2018). A review on cable-driven parallel robots. Chinese Journal of Mechanical Engineering, 31(1), 1-11. https://doi.org/10.1186/s10033-018-0267-9
7. Cafolla, D., Russo, M., & Carbone, G. (2018). Design and validation of an inherently-safe cable-driven assisting device. Int. J. Mech. Control, 19(01), 23-32.
8. Russo, M., & Ceccarelli, M. (2020). Analysis of a Wearable Robotic System for Ankle Rehabilitation. Machines, 8(3), 48.. https://doi.org/10.3390/machines8030048
9. Andrade, R. J., Freitas, S. R., Hug, F., Le Sant, G., Lacourpaille, L., Gross, R., & Nordez, A. (2018). The potential role of sciatic nerve stiffness in the limitation of maximal ankle range of motion. Scientific reports, 8(1), 1-10. https://doi.org/10.1038/s41598-018-32873-6
10. Miao, Q., Zhang, M., Wang, C., & Li, H. (2018). Towards optimal platform-based robot design for ankle rehabilitation: the state of the art and future prospects. Journal of healthcare engineering, 2018. https://doi.org/10.1155/2018/1534247
11. Huston, R. L. (2013). Fundamentals of biomechanics (p. 512). Boca Raton, FL. CRC Press.