Analysis of a Novel Design of a three-degree of Freedom Hip Exoskeleton Based on Biomimetic Parallel Structure

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***Abstract*—this research develops and analyzes a new three-degree of freedom parallel robotic structured hip exoskeleton. Compared with a typical exoskeleton designed as a serial mechanism for the entire leg or entire body, the parallel mechanism is a structure only for the hip. The parallel manipulator is more stable, stronger and provides more accurate movement than existing manipulators. A kinematic analysis is performed and an exhaustive mobility analysis and inverse kinematic solution are derived in closed form.**

Keywords-three degrees of freedom; PUU; inverse kinematics, Stiffness analysis, deformation, CAD

I. INTRODUCTION

Robots are classified into different categories based on various criteria. The most comprehensive one is based on the kinematic structure – serial robots, parallel robots, and hybrid robots which are the combination of the first two [1].

More and more parallel mechanisms are chosen because the percent demand to move heavy mass has decreased; instead, high dynamic performance and high stiffness are requested. As a result, the development of the parallel kinematic mechanism is under a high speed right now, so the parallel kinematic mechanisms are going to play a much more important role in the robotic paradigm in several years. That is because these parallel structure based machine tools offer better stiffness, higher acceleration, accuracy, reconfiguration and precision [2]. Because of these attributes, parallel kinematic mechanisms are widely used in biomechanics, such as exoskeleton. There are three principal areas that biomechanics are generally divided into: performance, injury, and rehabilitation [3]. However, this criterion is not strict – some biomechanics have the future that fits all three areas. Based on verity of requirements, different kinematic structures are picked to build different kinds of exoskeletons.

II. DESIGN REQUIREMNTS

The primary purpose for developing this manipulator is to provide the wearers the assistant they need during normal gait.

In short, the designed hip exoskeleton has to be designed to satisfy all the following requirements:

1. Including a parallel robotic structure;
2. At least a three-degree of freedom (3DOF) tripod design and integration for the assistance robot in order to move forward, backward, and sideway;
3. As accurate as possible while operating;
4. Enough stiffness;
5. As light as possible for easy walking around;
6. Adjustable;
7. Easy to wear/take off;
8. Easy to assemble;
9. Reasonable performance of the robotic assistance systems;
10. Modular design for repair convenience.

III. HIP EXOSKELETON GEOMETRIC STRUCTURE

To build the CAD model, a specific wearer needs to be selected because the human data is going to be refereed. This data are reasonably close to that of the MIT test participant who was of the same age [4].

TABLE I. SUMMARY OF HUMAN DATA FOR DESIGN

Elements	***Unit***	***Dimensions***
Age	year	30
Sex	male	-
Height	cm	178
Weight	Kg	85
Waist size	cm	130
Top part of the thigh size	cm	58
Low part of the thigh size	cm	50
Leg length	cm	100
Walking speed	m/s	0.65±0.15

A. Position Analysis

The movement of the hip for a regular walking motion is considered as a three-degree of freedom (3DOF) motion which is consisted by three motion planes (x-y plane, y-z

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plane, and x-z plane. Thus, the designed exoskeleton has to meet the following possible positions ranges in Table 2 in order to help people to achieve the possible average daily activities.

TABLE II. THE DESIGNED HIP ROM [3] [5]

Move Plane	*Motion*	*Maximum Displacement*	*Designed Displacement*
Sagittal Plane	Forward	60 degree	70 degree
	Backward	30 degree	35 degree
Coronal Plane	Up/Down	10 cm	15 cm
Transverse Plane	Outside	45 degree	50 degree
	Inside	20 degree	25 degree

B. *CAD Model*

The primary CAD model of the 3-DOF P-U-U parallel structure hip exoskeleton has been built with SolidWorks, which is shown in the following figure.

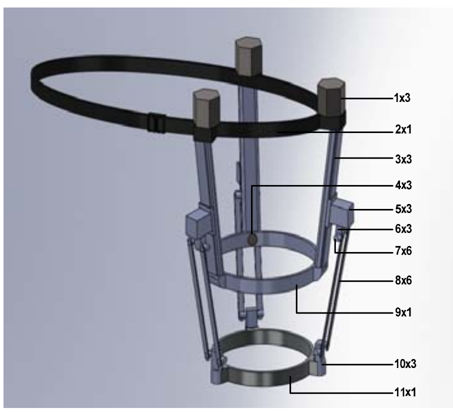

Figure 1: Upgrading CAD Model of the Hip Exoskeleton: (1) Motor (2)Waist Belt (3) Upper leg (4)Sensor connecting point (5) Leg joint (6)Upper leg joint (7)Screw (8) Lower leg(9) Upper leg belt (10) Lower leg joint (11) Lower leg belt

This model is built by taking a regular size person as a dimension reference in Table 1. As the figure shown, the top part is the waist belt that will be fixed on patient's waist, and the size of the belt can be adjusted based on the size of waist of the operator. As a result, the full amount weight of the kinematic machine will be carried on the patient's waist for the current design.

IV. KINEMATICS ANALYSIS

A. *Mobility Analysis*

The degrees of freedom (DOF) of a mechanism are the number of independent parameters or inputs needed to specify the configuration of the mechanism completely. The DOF value of a mechanism or mobility determination can be examined by using the Chebychev-Grübler-Kutzbach's formula [6]:

$$M = \delta(\nu - \gamma - 1) + \sum_{\iota=1}^{\gamma} \varphi_{\iota} \qquad (1)$$

Where:

M : Degrees of freedom of a mechanism,

d : DOF of the space in which a mechanism is intended to function (for planar motion, and for spatial motion),

n : Number of links in a mechanism, including the fixed link,

g : Number of joints in a mechanism, assuming that all joints are binary,

f_i : Degrees of relative motion permitted by joints .

This parallel hip exoskeleton can be simplified as a 3 PUU (prismatic, universal, and universal) joints manipulator. A prismatic joint has one degree of freedom and imposes five constraints between the paired elements, and a universal joint has 2 degree of freedom because it is a combination of two intersecting revolute joints [1]. As a result, each limb of the manipulator has:

$$f_i = 1+2+2 = 5\ DOFs \qquad (2)$$

By analyzing this schematic diagram, we can get the DOF of the hip exoskeleton is three by applying the Chebychev-Grübler-Kutzbach's formula,

With d =6; n = 8; g = 9; f_i = 5,

$$M = 6\times(8-9-1)+3\times(1+2+2) = 5$$

$$M = 6\times(8-9-1)+3\times(1+2+2) = \qquad (3)$$

From the simplified schematic diagram in Figure 2, we can see that this manipulator has tow platforms, the base platform, B1B2B3, and the end-effector moving platform, A1A2A3. The end-effector platform moves by taking the reaction from the bottom universal joints which connected to the bottom legs of the manipulator [7].

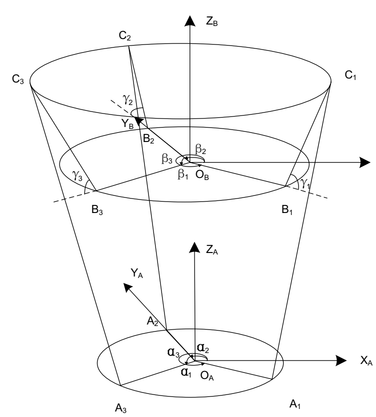

Figure 2: Simplified Schematic Diagram of the Hip Exoskeleton Unit

Dr. Lung-Wen Tsai indicates that a parallel manipulator is classified as symmetrical if it satisfies the three conditions which are [1]:

- The number of limbs is equal to the number of degrees of freedom of the moving platform;

- The type and number of joints in all the limbs are arranged in an identical pattern;
- The number and location of actuated joints in all the limbs are the same.

Parallel mechanisms are grouped into three categories in general: planar, spherical, and spatial mechanisms. The connectivity of a limb, C_k, is a bright criterion to enumerate and classify parallel manipulators by applying the Connectivity [1].

$$\sum_{k=1}^{m} C_k = (\lambda + 1)M - \lambda$$

$$\boldsymbol{M = 6 \times (8 - 9 - 1) + 3 \times (1 + 2 + 2) =} \quad (4)$$

With a condition of that the connectivity of a limb should not be greater than the motion parameter and less than the DOF of the moving platform, which is (16):

$$M \le C_k \le \lambda$$

$$\boldsymbol{M = 6 \times (8 - 9 - 1) + 3 \times (1 + 2 + 2) =} \quad (5)$$

Where:

M: is the numbers of degrees of freedom;

λ: is the degree of freedom of the space in which a mechanism is intended to function;

Ck: is the system connectivity.

m: is the number of limb

In this paper, the manipulation has 3 DOF and three limbs, so λ =3, M=3. Substituting λ and M into Eq. (4) and (5), we get

$$C_1 + C_2 + C_3 = 4M - 3 = 9$$

$$\boldsymbol{M = 6 \times (8 - 9 - 1) + 3 \times (1 + 2 + 2) =} \quad (6)$$

And

$$3 \le C_k \le 3 \qquad (7)$$

Therefore, the connectivity of each limb should be equal to 3, which means that each limb should have 3 DOF in its joints. This manipulator is a planar parallel manipulator. Overall, the P-U-U structure of the hip exoskeleton is feasible based on the above calculation.

B. Inverse Kinematic Analysis

The purpose of the inverse kinematic analysis is to initialize the movement of the actuator from a given position of the mobile platform [8].

The position vectors of points Ai and Bi with respect to platforms A and B can be written as

$${}^{A}a_i = \left[a_i \cos\alpha_i, a_i \sin\alpha_i, 0\right]^T \qquad (8)$$

$${}^{B}b_i = \left[b_i \cos\beta_i, b_i \sin\beta_i, 0\right]^T \qquad (9)$$

So the actuator vector u_i on the base platform and the end-effector position vector p can be expressed as

$$u_i = \left[u_i \cos\gamma_i \cos\beta_i, u_i \cos\gamma_i \sin\beta_i, u_i \sin\gamma_i\right]^T \qquad (10)$$

$$p = \left[p_x, p_y, p_z\right]^T \qquad (11)$$

The inverse kinematics analysis is to determine the displacement of the actuated variables for a known position and orientation of the end-effector. The joint motions can be derived from this vector loop as shown in Eq. (12).

$$l_i = a_i + p_i - b_i - u_i = \begin{bmatrix} a_i \cos\alpha_i + p_x - b_i \cos\beta_i - u_i \cos\gamma_i \cos\beta_i \\ a_i \sin\alpha_i + p_y - b_i \sin\beta_i - u_i \cos\gamma_i \sin\beta_i \\ p_z - u_i \sin\alpha_i \end{bmatrix} \qquad (12)$$

However, the solution in this paper means the motion of the vector between B_iC_i, which has to be the position number since it means the actuator is located above the translated leg and enhance the stiffness of the structure [9]. Also, Since A = 1 in this case, the solution of u can be defined as

$$u_i = \frac{-B \pm \sqrt{B^2 - 4C}}{2} \qquad (13)$$

Where:

$$\begin{cases} B = -2\left\{\cos\gamma_i \begin{bmatrix} \cos\beta_i(a_i \cos\alpha_i + p_x - b_i \cos\beta_i) \\ + \sin\beta_i(a_i \sin\alpha_i + p_y - b_i \sin\beta_i) \end{bmatrix} + (p_z \sin\gamma_i)\right\} \\ C = (a_i \cos\alpha_i + p_x - b_i \cos\beta_i)^2 + (a_i \sin\alpha_i + p_y - b_i \sin\beta_i)^2 + p_z^2 - l_i^2 \end{cases} \qquad (14)$$

After each u_i is solved, the translation of the entire manipulator is analyzed. A stiffness analysis can be developed from these results.

C. Stiffness Analysis

There are many elements which affect the stiffness of a mechanism. For a parallel mechanism, these elements are stiffness of the joints, the structure and materials of the legs and platforms, the stiffness of both platforms, the geometry of the structure, and the end-effector position and orientation [10]. This wrench can be any force or moment that causes deformations of the moving platform, which can be described by Eq. (15).

$$w = K\delta p \qquad (15)$$

Where:

K: is the generalized stiffness matrix;

w: is the wrench vector meaning the force or the torque that acts on the moving platform; and it is can be represented as $\boldsymbol{w} = \left[F_x \quad F_y \quad F_z \quad \tau_x \quad \tau_y \quad \tau_z\right]^T$;

δp : is the vector meaning the linear and angular deformation of the moving platform; and it is can be represented as $\delta p = \left[\dot{x} \quad \dot{y} \quad \dot{z} \quad \dot{\theta}_x \quad \dot{\theta}_y \quad \dot{\theta}_z\right]^T$.

The wrench vector that is caused by the force and moment applied on the actuators can also be described by the transpose of the Jacobian matrix J, which has been explained by J.P Merlet as the following equations:

$$w = J^T f \qquad (16)$$

$$\delta q = J\delta p \qquad (17)$$

Where yields:

f : is the vector represents the force or moment of the actuator;

δq : is the deformation of the actuator.

The force/torque and displacement applied on the actuator can be specified as Eq. (18) by Hookes' law.

$$f = K_J \delta q \tag{18}$$

Where: K_J is the actuator stiffness matrix in a diagonal form that is $K_J = \begin{bmatrix} k_1 & k_2 & k_3 \end{bmatrix}$, and k_1, k_2 and k_3 represent the joint stiffness of each actuator.

With the generated stiffness matrix K, it becomes:

$$K = J^T K_J J \tag{19}$$

By applying the above calculations into MatLab, the results of the stiffness of the hip exoskeleton are shown as in Figures 3 to 5.

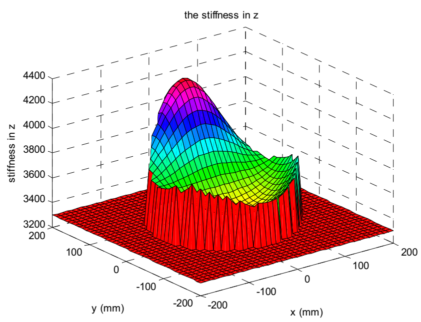

Figure 3: Stiffness Results in Z direction of the Hip Exoskeleton

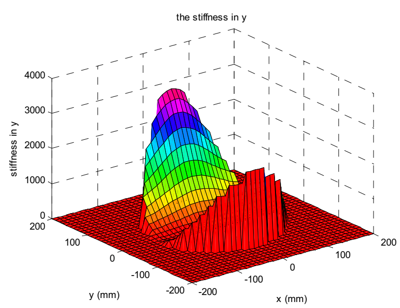

Figure 4: Stiffness Results in Y direction of the Hip Exoskeleton

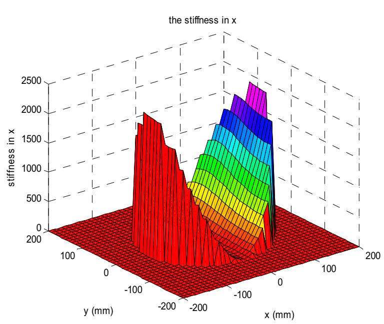

Figure 5: Stiffness Results in X direction of the Hip Exoskeleton

First, the above results have certified the symmetrical parallel structure that was introduced earlier. That is because each diagram shows that stiffness is symmetrical referring all x, y, and z-axis. Second, all three figures show that the results are controlled in a reasonable range, which means the stiffness of the hip exoskeleton structure is fully tested. Therefore, the design of the manipulator has a reliable structure regarding to the stiffness analysis.

V. CONCLUSION

This paper focuses on the analysis of the structure of this design, and verifies if the design has a reasonable and reliable structure. Therefore, a series of analysis has been done to support it. An exhaustive mobility analysis and inverse kinematic solution are derived in closed form based on a primary prototype which is built in SolidWorksOverall, this research has achieved the primary objective, which is to provide a parallel structure three-degree of freedom hip exoskeleton unit that helps wearers moving their legs properly.

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