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Research Paper

Mechanical Design of Exoskeleton for Hand Therapeutic Rehabilitation

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ABSTRACT : *In this study an exoskeleton is designed for hand in therapeutic rehabilitation. The mechanical design is manufactured in consideration of anthropometrical measurements of the hand studied from literature. Kinematic model of the hand exoskeletonwas obtained by results of position, velocity and torque-moment analysis. The exoskeleton has a single degree of freedom (DOF) for the PIP and MCP joints. Basic four-bar linkage mechanisms are used in the exoskeleton. With this design, while movements (flexion and extension) occurs in both joints at the same time, angular displacement come out as in healthy hands. Linkage lengths are optimized to achieve the targeted angular dynamics. The manipulation of the exoskeleton is actuated by a linear servo motor.*

KEYWORDS –*Exoskeleton, four bar, kinematic, velocity, force*

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I. INTRODUCTION

Therapeutic rehabilitation is frequently used in the treatment of lost motor function that occurs as a result of disease and injury. Usually the rehabilitation therapy is based on the manipulation of the paretic limb by a physiotherapist. Rehabilitation robots can be used in the process as a support to physiotherapists. The support of robots during the clinical rehabilitation or post-clinical home exercises provides a much more efficient healing process [1].

Rehabilitation processes are applied to eliminate deficiencies such as joint range of motion (ROM), muscle weakness and coordination. Robots designed for this purpose can manipulate end point of the limb or manipulate all the joints. Compared to end-effector designs with simple mechanical structure, exoskeleton-based designs are seen to be more advantageous for the rehabilitation of limbs with complex mobility. The design of the rehabilitation robot also depends on the actuators used for manipulation. For this purpose, electric motors are frequently used. In addition, pneumatic, hydraulic actuators can be used [2].

In recent decades, many laboratories have started projects with the main purpose to design robotic systems for hand rehabilitation. At Advanced Robotics (ADVR) Department Institute Italian Technologic, Hexosys was developed as a novel device for rehabilitation of the thumb and index finger. These exoskeletons incorporate passive force feedback in the control loop by applying forces to the wearer based on scheme of energy removal from the human machine interface [3].

Another exoskeleton was developed at “ARTS Lab ScuolaSuperioreSantanna” by Chiri and his colleagues. This device was developed for the rehabilitation of a hand post-stroke. The exoskeleton goal is to train a safe extension motion from the typical closed position of the impaired hand [4].

Wege and Hommel developed a hand exoskeleton which has four degrees of freedom which are actuated bidirectionally by the use of two Bowden cables and levers for each finger joint. On each lever, a hall sensor is attached to measure the angle of the finger joints accurately [5].

The BRAVO hand exoskeleton is an active hand orthotic conceived to support stroke patients in cylindrical grasping tasks. The device has two independent degrees of freedom, one for fingers and one for thumb, for assisting grasping of cylindrical objects. The hand exoskeleton is composed of five planar mechanisms [6].

Korea Advanced Institute of Science and Technology developed a low cost and light-weight device for comprehensive upper limb training including both arm and hand. This device has a 3 DOF gravity compensating tracker for the Glenohumeral (GH) joint. It also has a ring type exotendon which mimics four biological tendons of a finger [7].

In this study, simple bar mechanisms were used to produce complex flexion and extension movements. In addition, the motion data of the rehabilitation robot has been evaluated by comparison with healthy hand movement data.

II. DESIGN OF REHABILITATION ROBOT

For a healthy hand, the functional range of motion (fROM) of the fingers is -5^o to 77^o, 16^o to 93^o, and 1^o to 72^o for MCP, PIP and DIP joints, respectively. (Fig.1) Studies were shown that these functional range of motions are used in daily activities at rates of 48%, 59% and 60%, respectively [8]. The suitability of a hand-held rehabilitation robot to the hand anthropometry will positively affect usability and efficiency.

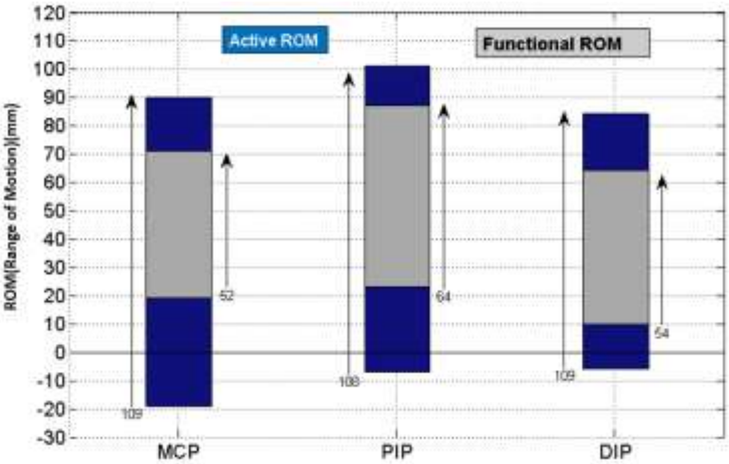

Figure.1 Active and Functional ROM of Hand

It is more appropriate to use a linear actuator against radial electric motors to manipulate the joints. While it is much easier to manipulate with a linear actuator, the relationship between angular displacement during manipulation of DIP, PIP and MCP joints during flexion or extension should also be considered. To establish this relationship, 4 bar mechanisms, which are frequently used in mechanics and stand out by its simple structure, was used. Using the angular relationship of the linkage mechanisms, desired motion trajectories are provided.

Fig 2 Hand Rehabilitation System

We designed a finger manipulator which is developed by basic linkage mechanisms. This mechanism is actuated by a linear actuator (Firgelli L12 stroke 50mm 100:1 gear ratio). The rehabilitation system provides onedegree of freedom (DOF) at the MCP joint and the PIP joint. Both of the joints can work at the same time. The maximum force exerted by the actuator is 23N and maximum speed is 12mm per second. For an actuator with a stroke length of 50mm, a full hand opening or closing action would take about 12 seconds. The MCP joint can move from fully extended position to 55 degrees, PIP joint can move from fully extended position to 65 degrees of flexion. As can be seen in the figure, the designed system can work in 80% of thefROM and 50% of theaROM (active ROM) for MCP joint and also 92% of the fROM and 76% of the aROM for PIP joint.

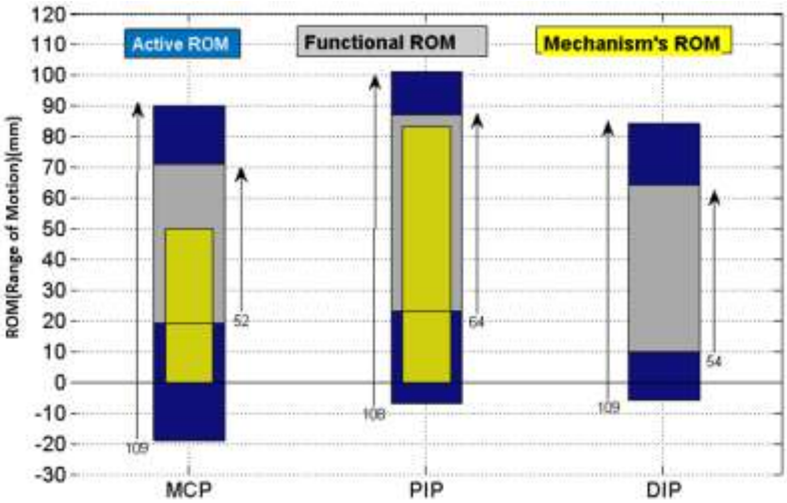

Fig 3. Active and Functional ROM of system

2.1 Position Analyses

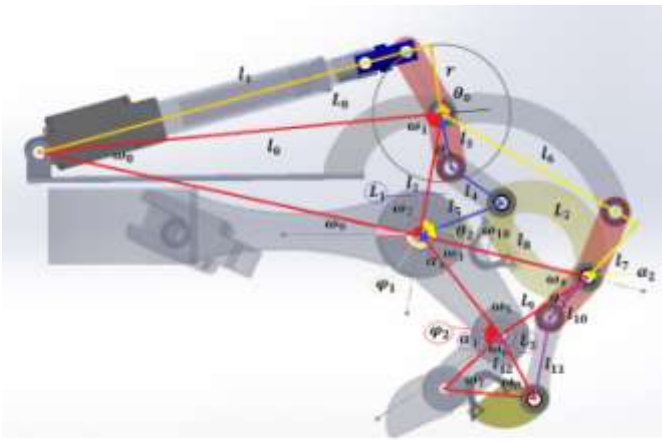

Fig 4. Kinematic dynamic of hand rehabilitation robot

The system is comprised of L_0, L_1, L_2, L_3 linkage mechanisms. Four linkage mechanisms have one degree of freedom. φ_1 and φ_2 angles are positioned depending on length l_1. θ_0 and θ_1 can be found by L_0 bar mechanism in terms of the following equation depending on the length l_1.

$l_1 = \sqrt{(l_0 + r * cos\theta_0)^2 + \left((sin\theta_0) * r\right)^2}$	(1)
$\theta_1 = arccos\left(\frac{l_1^2 - l_0^2 - (2r^2 + 2l_0 r)}{2l_1 r + 2r^2}\right) - \omega_1$	(2)

To find the angle α_1 with θ_1 angle and bar lengths on L_1

$-2l_3 l_5 sin\theta sin\alpha + 2l_5(l_2 - l_3 cos\theta)cos\alpha + l_2^2 + l_3^2 + l_4^2 + l_5^2 - 2l_2 l_3 cos\theta = 0$	(3)

If x_1, x_2 and x_3 are functions of θ, and

$x_1(\theta) = -2l_3 l_5 sin\theta$	
$x_2(\theta) = 2l_5(l_2 - l_3 cos\theta)$	
$x_3(\theta) = l_2^2 + l_3^2 + l_4^2 + l_5^2 - 2l_2 l_3 cos\theta$	
$x_1(\theta)sin\emptyset + x_2(\theta)cos\emptyset + x_3(\theta) = 0$	(4)

Eq. (4) is the well-known *Freudenstein equation*, which can be solved in closed form. This allows us to determine in terms of $\emptyset$ to solve Eq. (4), define:

$$t = tan\frac{\emptyset}{2} \tag{5}$$

We then arrive at the solution of:

$$t = \frac{-x_1 \pm \sqrt{x_1^2 + x_2^2 - x_3^2}}{x_3 - x_2} \tag{6}$$

Substituting Eq.(5) into Eq.(6), yields:

$$\alpha_1 = 2 * arctan(\frac{-x_1 \pm \sqrt{x_1^2 + x_2^2 - x_3^2}}{x_3 - x_2}) \tag{7}$$

From hence;

$$\theta_2 = (\pi - \alpha_1) + \omega_{10} \tag{8}$$

To find the angle α_2 and $\theta_3$with θ_2 angle and bar lengths on L_2 with same process like Eq.(4).

$$\alpha_2 = fun(\theta_2, l_2, l_6, l_7, l_8)$$

$$\theta_3 = \alpha_2 - \omega_4 \tag{9}$$

To find the angle α_3 with θ_3 angle and bar lengths on L_3 with use Eq.(4).

$$\alpha_3 = fun(\theta_3, l_9, l_{10}, l_{11}, l_{12}) \tag{10}$$

From hence;

$$\begin{aligned} \varphi_1 &= 2\pi - (\theta_2 + \omega_3 + \omega_2 + \omega_9) \\ \varphi_2 &= 2\pi - (\omega_5 + \omega_6 + \pi - \alpha_3) \end{aligned} \tag{11}$$

The MCP and PIP joint angle changes of the designed rehabilitation system are shown together with the MCP and PIP joint angles, which are measured after the cylinder hand grasp experiments with a healthy hand in Figure 5 [9]. The angular changes of the joints in the rehabilitation system relative to each other and the comparative angular changes obtained from the cylinder gripping experiment are shown in Fig.6.

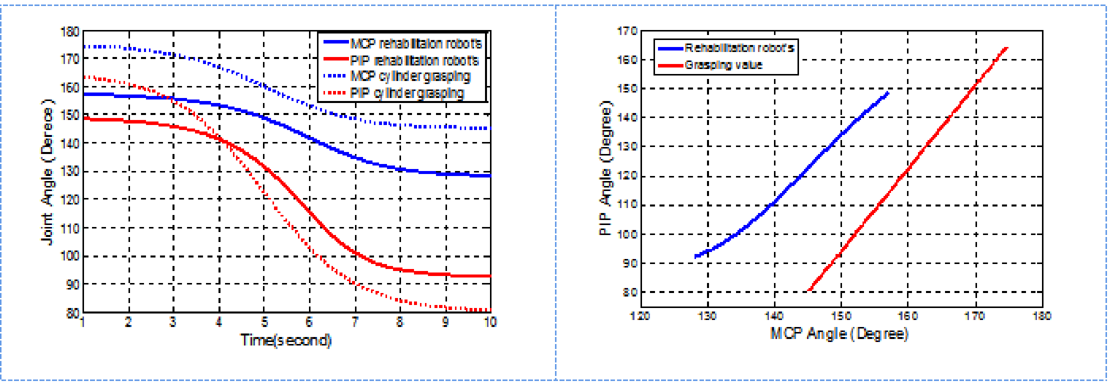

Fig 5. Angular displacement of flexion

2.2 Velocity Analyses

In the velocity analysis, differentiating the loop-closure constraints in Equation (3) with respect to time and expressing them in matrix form yield.

$$\underbrace{\begin{bmatrix} l_1 sin\theta & l_2 sin\alpha & -l_3 sin\emptyset \\ -l_1 cos\theta & -l_2 cos\alpha & l_3 cos\emptyset \end{bmatrix}}_{A} \begin{bmatrix} \dot{\theta} \\ \dot{\alpha} \\ \dot{\emptyset} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{12}$$

Since we choose θas the independent variable, we arrange Equation (12) into the following

$$\begin{bmatrix} l_2 sin\alpha & -l_3 sin\emptyset \\ -l_2 cos\alpha & l_3 cos\emptyset \end{bmatrix} \begin{bmatrix} \dot{\alpha} \\ \dot{\emptyset} \end{bmatrix} = \begin{bmatrix} -l_1 sin\theta \\ l_1 cos\theta \end{bmatrix} \dot{\theta} \quad (13)$$

And obtain:

$$\begin{bmatrix} \dot{\alpha} \\ \dot{\emptyset} \end{bmatrix} = \begin{bmatrix} S_1(\theta,\alpha,\emptyset) \\ S_2(\theta,\alpha,\emptyset) \end{bmatrix} \dot{\theta} \quad (14)$$

Where S= $\begin{bmatrix} S_1(\theta,\alpha,\emptyset) \\ S_2(\theta,\alpha,\emptyset) \end{bmatrix}$ is the null space of matrix A and

$$S_1(\theta,\alpha,\emptyset) = \frac{\partial\alpha}{\partial\theta} = \frac{l_1 \sin(\emptyset-\theta)}{l_2 \sin(\alpha-\emptyset)}$$
$$S_2(\theta,\alpha,\emptyset) = \frac{\partial\emptyset}{\partial\theta} = \frac{l_1 \sin(\alpha-\theta)}{l_2 \sin(\alpha-\emptyset)} \quad (15)$$

The velocity $\dot{\theta}_1$in terms of $\dot{l}_1$determine by solves L_0 basic crank mechanism.The velocity $\dot{\varphi}_2$in terms of $\dot{\theta}_1$determined by Equation (16).

$$\frac{\dot{\varphi}_2}{\dot{\theta}_1} == \frac{\partial\varphi_2}{\partial\theta_1} = \frac{l_3 \sin(\emptyset_1-\theta_1)}{l_5 \sin(\emptyset_1-\alpha_1)} * \frac{l_2 \sin(\emptyset_2-\theta_2)}{l_7 \sin(\emptyset_2-\alpha_2)} * \frac{l_{10} \sin(\emptyset_3-\theta_3)}{l_{12} \sin(\emptyset_3-\alpha_3)} \quad (16)$$

The angular velocity values obtained from a healthy hand and the angular velocity values generated during the flexion of the rehabilitation robot are shown together in Fig. 6.

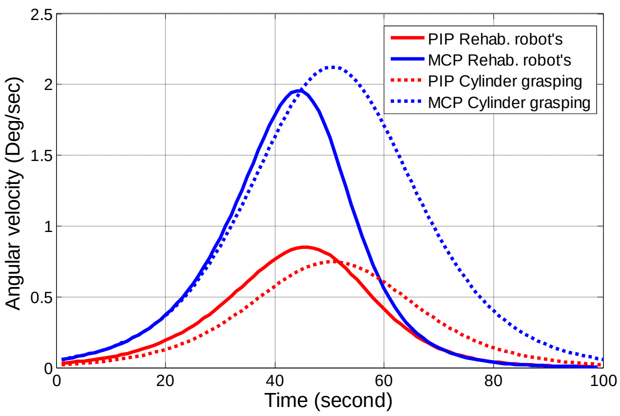

Fig. 6 Angular Velocity of flexion

2.3 Torque-Moment Analysis

The mathematical force-moment model of the hand rehabilitation system is created with basic Newton equations for the effect of the force generated in the linear actuator, the torque generated in the joints and the contact forces occurred in the phalanges. The masses of the bars and other components were neglected when this model was constructed. The contact force applied to the proximal phalanx and the torque variables in the MCP joint are shown in Fig. 7.

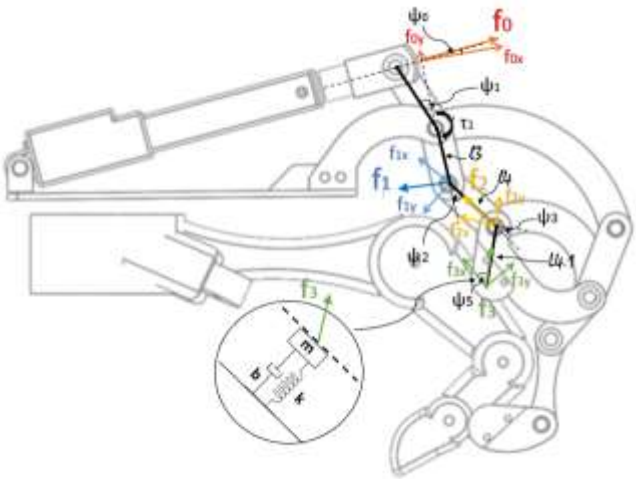

Fig 7. Force-moment model for proximal phalanges

All of the forces shown in Fig. 8 along with the force generated by the linear actuator are shown in Equation 17.

$$\begin{bmatrix} f_0 \\ f_1 \\ f_2 \\ f_3 \end{bmatrix} = \begin{bmatrix} f_{0x} & f_{0y} \\ f_{1x} & f_{1y} \\ f_{2x} & f_{2y} \\ f_{3x} & f_{3y} \end{bmatrix} * \begin{bmatrix} \cos(\psi_0) & \cos(\psi_2) & \cos(\psi_3) & \cos(\psi_4) \\ \sin(\psi_0) & \sin(\psi_2) & \sin(\psi_3) & \sin(\psi_4) \end{bmatrix} \quad (17)$$

The torque τ_1 produced by the force f_0 that applied by the linear actuator is given in Eq. 18.

$$\tau_1 = f_{0x} * r * cos(\psi_1) + f_{0y} * r * sin(\psi_1) \quad (18)$$

The torque that worked on MCP joint as a function of τ_1 produced by the linear actuator for the entire system is as Equation (19).

$$\tau_{mcp} = \frac{\tau_1 * \cos(\psi_2) * sin(\psi_3) * sin(\psi_4) * p_1}{l_3} \quad (19)$$

Figure 8 demonstrates the application of 50N of force by the linear actuator for flexion 135.5 mm to 140 mm, τ_{mcp} torque produced on the MCP joint.

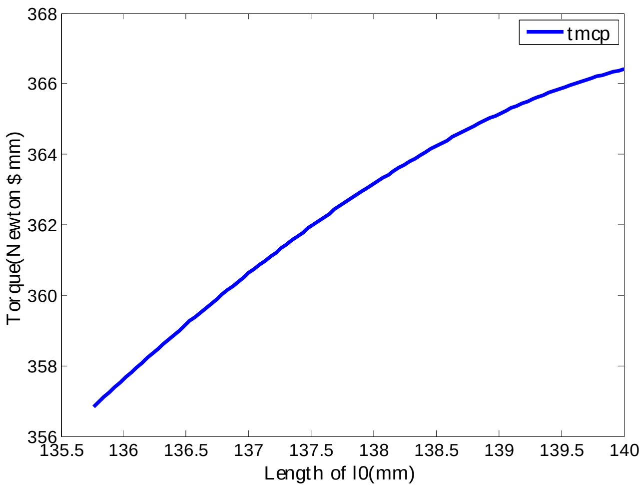

Fig 8. Graph of torque of the MCP joint

The contact forces on the proximal phalanx are the f_{3x} and f_{3y} forces shown in Eq. 20.

$f_{3x} = \frac{\tau_1 * \cos(\psi_2) * sin(\psi_3) * cos(\psi_4)}{l_3}$,	(20)
$f_{3y} = \frac{\tau_1 * \cos(\psi_2) * sin(\psi_3) * sin(\psi_4)}{l_3}$	

The contact forces calculated by the fixed 50 N actuator force when rehabilitation robot works for flexing 135.5 mm to 140 mm l_0 lengths are shown in Fig.9.

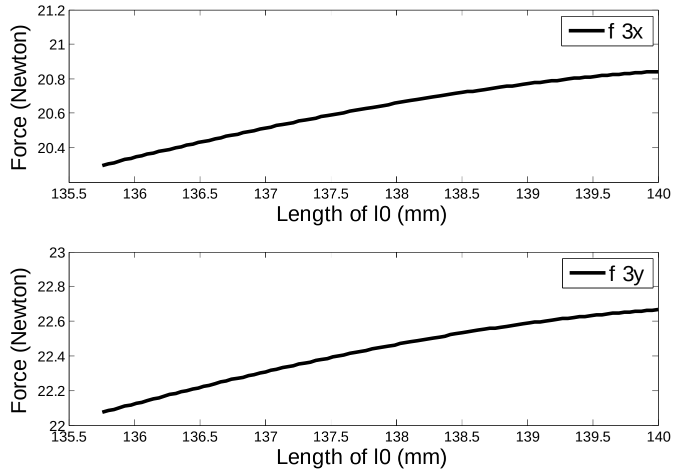

Fig 9. Graph of the contact force on proximal phalanx

f_{3y}, which is perpendicular to the proximal phalanx, produces the torque shown in Equation (24). In contrast, the f_{3x} force works against the binding force in the perpendicular direction to the phalanx. This force causes an undesired shear force on the patient's finger at the tether point.

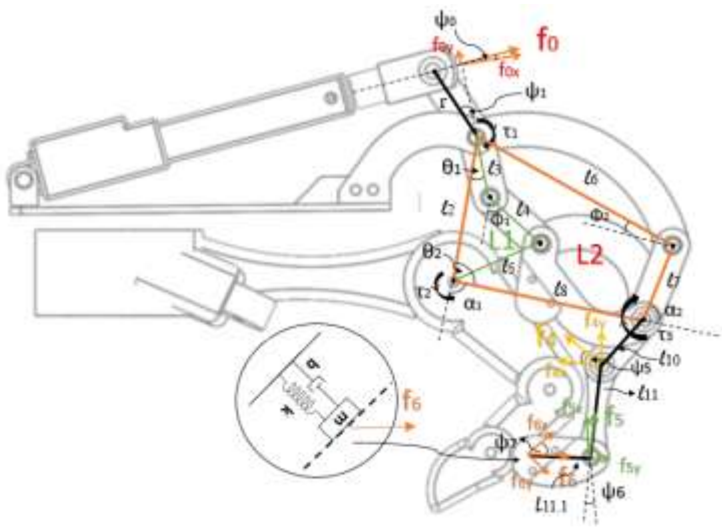

Fig 10. Force-moment model for intermediate phalanges

τ_1 torque produces torque τ_2 on the MCP joint with the *L1* four-bar mechanism as follows [1];

$\tau_2 = \tau_1 * \left(\frac{l_3 * \sin(\theta_1 - \phi_1)}{l_5 * \sin(\alpha_1 - \phi_1)}\right)$	(21)

The calculated torque $\tau_2$produces torque τ_3 with the four-bar mechanism *L2* and produces contact force (f_6) in the intermediate phalanx as follows;

$\tau_3 = \tau_2 * \left(\frac{l_2 * \sin(\theta_2 - \phi_2)}{l_7 * \sin(\alpha_2 - \phi_2)}\right)$	(22)

The torque force generated in the PIP joint with the calculated torques can be write as in equation 4.28.

$\tau_{pip} = \frac{\tau_3 * \sin(\psi_5) * \sin(\psi_6) * sin(\psi_7) * p_2}{l_{10}} *$	(23)

Figure 11 demonstrates the application of 50N of force by the linear actuator for flexion 135.5 mm to 140 mm, τ_{mcp} torque produced on the PIP joint.

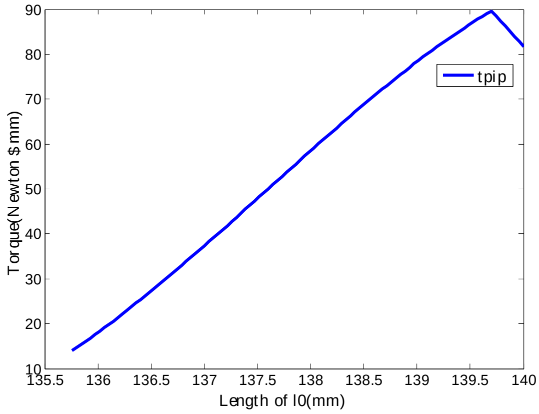

Figure 11. Graph of torque of the PIP joint

The contact force on the medial phalanges can be calculated as f_{6y} and f_{6x} as shown in Fig.

$f_{6x} = \frac{\tau_3 * \sin(\psi_5) * \sin(\psi_6) * cos(\psi_7)}{l_{10}}$, $f_{6y} = \frac{\tau_3 * \sin(\psi_5) * \sin(\psi_6) * sin(\psi_7)}{l_{10}}$	(24)

The contact forces calculated by the fixed 50 N actuator force when rehabilitation robot works for flexing 135.5 mm to 140 mm l_0 lengths are shown in Fig.12.

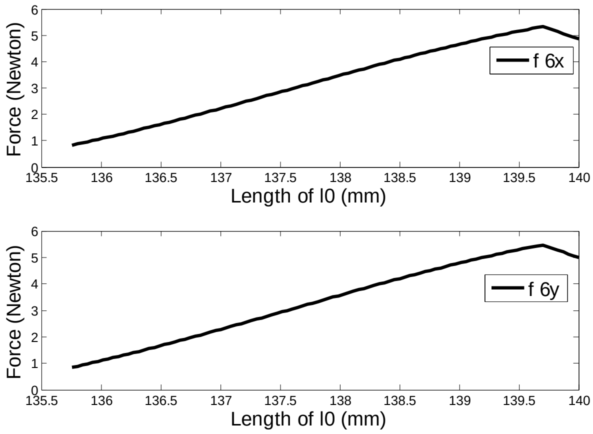

Fig 12. Graph of the contact force on intermediate phalanx

III. CONCLUSION

The exoskeleton designed for hand rehabilitation is fabricated as a prototype. The designed system is simpler than similar ones from aspect with the mechanical structure and the biodynamic fit of the hand.

The kinematic analysis of the designed system was conducted.Angular velocity and angular displacement of the movement of the system driven by linear servo motor were examined. These values are within the limits of range of motion in the literature, which shows what is ergonomic for human hands. In addition, force-torque analysis was conducted and mathematical model of the system was obtained.

In the future study, the hand rehabilitation robot will be evaluated by physiotherapists for clinical use and investigated for its usefulness by using the kinematic models obtained in this study. Control system will be designed by considering all these evaluations.

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