PROSTHETIC FINGER DESIGN WITH REDUCED DOF TO SYNONYM HUMAN FINGER

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INTRODUCTION

The human finger has three distinct sections which hinged in three joints. Different sections of the finger are Distal Phalanx (DP), Middle Phalanx (MP), Proximal Phalanx (PP) and the joints are Distal Inter-phalangeal (DIP) joint, Proximal Inter-phalangeal (PIP) joint, Metacarpal phalangeal (MCP) joint.

As per the day to day requirements, humans do not use the PIP and DIP motions separately. Most people cannot control them separately even desired, as it was not required and thereby not practiced by human beings. Therefore, the actual human finger operation is only two DOF using three separate inputs where the PIP and DIP works in combination.

This phenomenon has opened an opportunity to reduce the DOF to two in designing prosthetic arms and reduce the sEMG or similar input requirements from the user, while keeping the motion of the fingers close to natural movements. By allowing a reduced DOF, it enables the prosthetic arm to use lesser number of sEMG inputs. Also this will be more similar to the commands given to the actual arm by brain. As a result, it will be easy for the people who lost an arm after their birth to practice with the replaced prosthetic arm.

This paper discusses about a novel way of combining the PIP joint and MCP joint such that the two movements are combined to a single movement pattern similar to the actual human finger movement.

PIP joint and MCP joint were connected by a swing arm mechanism that combines their motions, and the torque input operating the PIP joint operates the MCP joint too. A detailed analysis of the actual arm and its dynamic analysis was used to design the joints mechanism of prosthetic arm. After the design, the actual arm and prosthetic arm motions were simulated and compared to check the similarity of the two motions.

[Gizmodo et. el] discusses about a similar approach in his research the PIP joint and DIP joint movements are combined and how they can achieve a human like motion pattern. The paper has a crank slider and the generalized dynamic motion data. But the paper lacks motion comparison with the actual finger and talks about a different mechanical model than discussed within this paper. Also it relies on the linear motion mechanism which can be bulky and expensive to implement.

Most of the prosthetic finger designs and publications talk about separate actuator for DIP joint or no controlled motion. This paper distinguishes among them in that it achieves the human like motion without extra actuator at DIP which compares well with the human finger motion pattern and customizable according to the individual's exact finger motion pattern.

The contribution of this paper is a novel and customizable DIP and MCP joint interface with a similar motion pattern to the actual human finger to reduce the DOF of prosthetic fingers and hence reduce the learning curve of the users.

METHODOLOGY

Human Finger Movement Analysis

The human fingers can move directions defined as abduction and adduction, flexion and

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extension as shown in Figure 1. Usually humans do not use Active and Passive extension, and also barely uses Adduction and Abduction in day to day life. Hence the prosthetic fingers do not require motions such as Active/Passive extension and Adduction/Abduction.

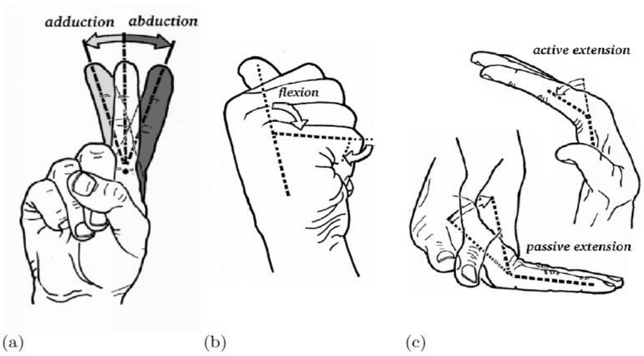

Figure 1. (a) Adduction/Abduction, (b) Flection, and (c) Active/Passive extension of human fingers [Kamper]

The Human index finger consists of the joints and distinct section as shown in Figure 2.

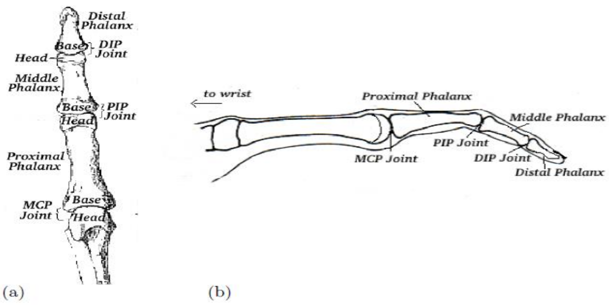

Figure 2. (a) Palmar and (b) Lateral views of the bones and joints of the human index finger [Kamper]

Kamper [1] discusses about a detailed analysis of human finger motions in actual scenarios. They have used motion capture system in Qualisys Track Manager Software (QTM) to individually measure the joint movements. The captured data includes real time monitor and record of position, angle, velocity and acceleration of each data point. The Motion Capture System (MOCAP) was used to animate the recorded motion and test the skeletal parameters. Notable usage of MOCAP is in the study of skeletal parameter by Kirk [6].

These data have been used to measure the fingertip motion profile and plot the motion (Figure 4). Also the same system was used to measure the angles of PIP joint vs. MCP joint and angles of DIP joint vs. PIP joint angles. This analysis offers the very important relationship between these joints in actual motions. As clearly seen in Figure 4 (b), the relationship between MCP and PIP is not clear and consistent, making them two independent joints. But the relationship between PIP and DIP joints is clear and follows the same line, making them highly correlated.
Therefore, the argument of this paper is that these joints can be combined yet having a same kind of human-like motion is well proven with this analysis.

When analyzing the finger motion, the start (initial) position was considered to be the maximum open position where the DP, MP and PP parts are kept in a single line. Then all the angles measured are towards the finger bending direction.

The captured fingertip movement trajectory for a finger motion while engaged in general activities is mapped and plotted in Figure 3 [1]. This motion is a collaborative motion of all the three joints, where the captured collaboration of the joints is shown in Figure 4.

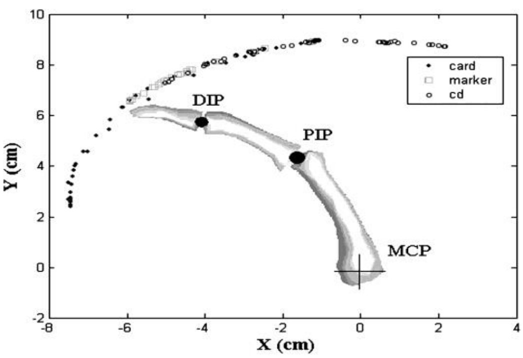

Figure 3. Trajectory of tip of index finger in the *x-y* pilne for 3 different trials: grasping the marker, the CD, or the playing card [1].

Figure 4. shows the relationship plot between DIP vs PIP joints (A) and PIP vs. MCP joints (B). These relationships were captured using 50Hz sampling of finger movement at general daily activities a Cyber Glove [7]. (Immersion Corp., San Jose, CA).

The results obtained by Kamper et. al. [5] is very important for this paper as is offers a baseline of biodynamic data of actual finger movements and joint's relationships. Therefore, the research data [1] was used to this study as a reference baseline to match the designed prosthetic finger.

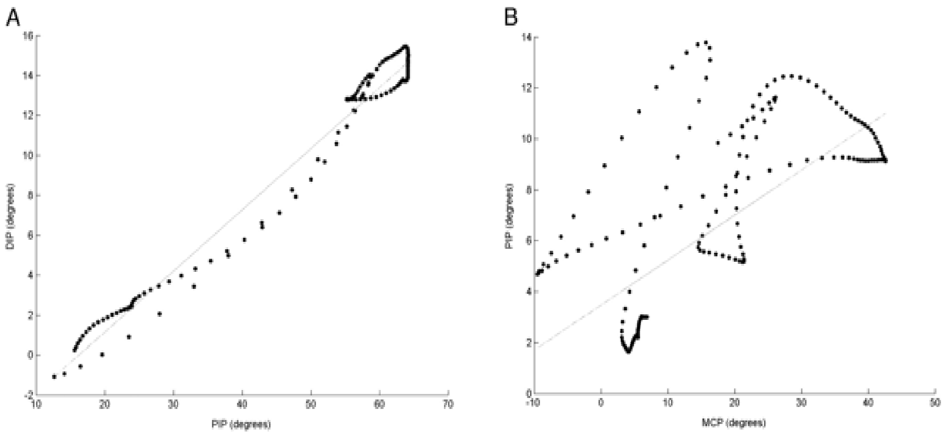

Figure 4. Relation between PIP and DIP joints (A) and relation between IPI and MCP joints (B) in actual human motion[5].

Designed Model and Development of PP and DP joint relationship

The finger model was analyzed, designed, simulated and implemented to synonym the actual finger movement. To achieve this task, first the general kinematics was used to determine the required motion and DOF. Then an easy-to-manufacture swing arm design was suggested to join the PIP and DIP joint motions. Equations were built using trigonometry to calculate the relationship between PIP and DIP joints using the developed model. These equations were fed to MatLab along with the extracted data from [1] to optimize the design parameters and make the design finger movements as equal as possible to the actual finger. Then, the designed and optimized model was ported to SolidWorks to simulate the motion. Finally, a model finger was designed and manufactured to test the actual finger movement and test the simulation results.

Kinematics and dynamics

As shown in Figure 5, finger kinematic model can be divided into three joints as Metacarpophalangeal joint (MCP) with two DOF alone X and Y axis, proximal Interphalangeal (PIP) joint with one DOF and distal Interphalangeal (DIP) joint with one DOF. But for the scope of this research, Y axis motion of MCP joint was neglected and was not implemented in designed models. But some of these joints work in conjunction in the actual human behavior [8]. Especially for the DIP and PIP joints, the relationship between the two joints can be approximated as $\theta_{DIP} = (2/3)\ \theta_{PIP}$ [8]. But as proven before [1], this approximation is a little shifted from the actual scenario when the actual finger movements were measured in real life situations.

Based on the biodynamic analysis on the actual finger [1], motion angles of each joint were limited to the following values.

$0^0 \leq \theta_{PIP\_FLEXION} \leq (90^0 \sim 100^0)$, $0^0 \leq \theta_{DIP\_FLEXION} \leq 90^0$, $0^0 \leq \theta_{MCP\_FLEXION} \leq 90^0$

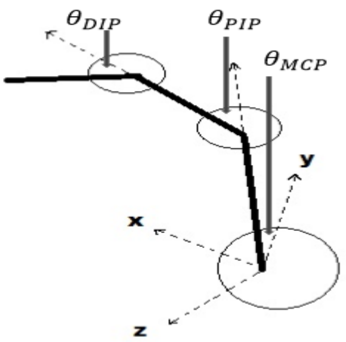

Figure 5. Kinematic model of human index finger.

Figure 6 shows the mechanism used to join the PIP and DIP joint motions by using a swing arm to connect the DP and MP arms. This will interlink the motion between PP and DP arms. Therefore, the DIP joint can automatically be driven from the PIP joint using a single actuator. This mechanism has five variables that can be adjusted to obtain the required relationship between PIP and PIP joints. These variables are shown in Figure 7 and Equation 4. By adjusting these variables individually or using simulation software to optimize the variables to the required PIP vs. DIP graph, the actual finger motion can be duplicated with one lesser actuator and DOF. The result of this implementation is shown in Figure 10, it shows the comparison of the actual finger movement and designed prosthetic finger movement.

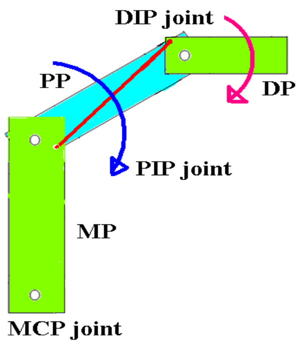

Figure 6. Finger movement PP and DP joints.

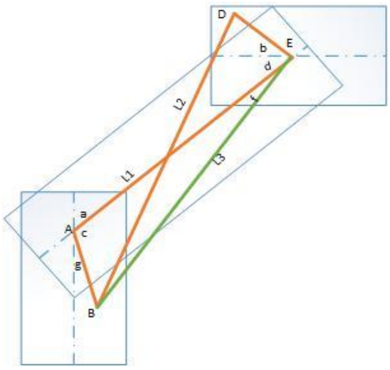

Figure 7. Finger movements PP and DP relationship.

The figure 7 shows the triangle model of the PP and DP joints that are used for building the equations. This model was used with equations (1), (2), (3) and (4) to build the mathematical relationship between the PP joint angle (a) and DP joint angle (d).

In figure 7, L1 is the PIP joint length, L2 is the swing arm length, x1 is AB length (from PP joint to swing arm mounting length), x2 is DE length (from DP joint to swing arm mounting length), ‘a’ is the PP joint angle, ‘d’ is the DP joint angle, ‘g’ is the swing arm mounting angle at PP joint and ‘b’ is the swing arm mounting angle at DP joint.

Using the general trigonometry for triangle ABE,

$$L_3^2 = X_1^2 + L_1^2 - 2X_1L_1\cos(c) \qquad (1)$$

And from triangle ABE,

$f = \cos^{-1}[(L_1^2 + L_3^2 - X_1^2) / 2L_1L_3]$ (2)

From triangle BDE,

$L_2^2 = X_2^2 + L_3^2 - 2X_2L_3\cos(b + d + f)$ (3)

Therefore, using equations (1),(2) and (3), the DP joint angle ‘d’ can be calculated using DP joint angle ‘a’ and other fixed values x1, x2, L1, L2, b as,

$d = \cos^{-1}[(X_2^2 + L_3^2 - L_2^2) / 2X_2L_3] - b - f$ (4)

These resultant equations and the relationship between ‘a’ &‘d’ were used for simulation of finger movements, optimization of input variables for finger-like movement and finally to build the optimized models.

SIMULATION, IMPLIMENTATION, TESTING AND COMPARISION RESULTS

With the development of mathematical model, a 3D CAD design was done to check the movement of fingers using Solidworks CAD software. This model offered a secondary method to prove the design by actually simulating the model and observing the finer-like motion. This CAD simulation results are shown in Figure 8.

Figure 8. CAD Design and simulation of Finger movements

Figure 9. Implemented finger and its PP & DP joint movements

Figure 9 shows the first finger prototype built to prove the functionality of the calculated and simulated model. The values calculated using MATLAB for optimize the finger movements and the values were used for build the prototype. The fabricated prototype was moved along with the actual fingers to check the accuracy and tolerances between the actual finger movements.

Actual test data from the biodynamic models [5] and equations (1),(2),(4) from the designed prosthetic finger were implemented in MatLab and the output plots were shown in Figure 10 to compare the relations between PP and DP joints. Using MatLab simulator, the design parameters of prosthetic finger were optimized to match the DP and PP relationship with the actual finger. Final result of DP and PP joint relationship was achieved by changing the design parameters as shown in Figure 10. These graphs show similar movements and relationships between PP and DP joints, and prove the concept of ability to reduce one DOF from fingers without restricting the motion of fingers.

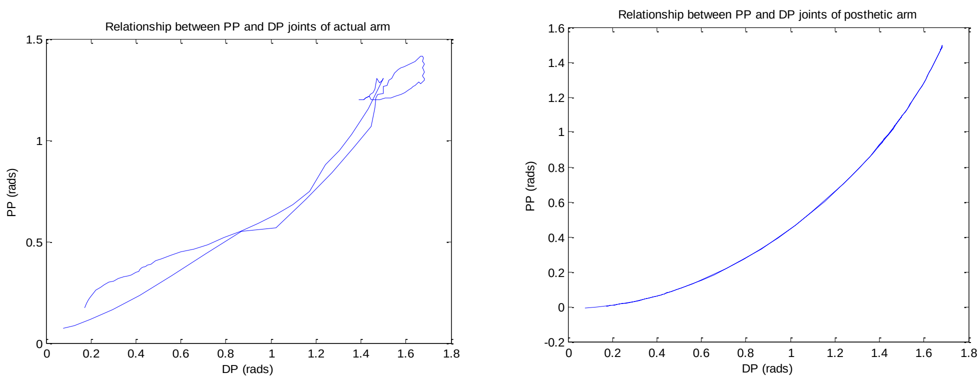

Figure 10. Plot of measured PP vs DP angles [5] and calculated PP vs DP angles as per equations (1), (2), (4) for x1 = 1, x2 = 0.5, L1 = 5, L2 = 6, b = 2.45 rads.

CONCLUSION AND FUTURE WORKS

In this paper, a new method of combining PIP and DIP joints to achieve human finger –like motion without an extra DOF is discussed. The proposed mechanism of swing arm, developed equations, simulations to optimize the parameters and actual prototyped finger was demonstrated.

A comparison between actual finger motion and designed finger model is performed. This research achieved a significantly similar motion to the actual finger using a very simple and low cost swing arm based solution. Also the equations (1) to (4) enable changing the parameters and achieving the required motion profile for any given finger.

As the future developments, the following tasks and researches can be conducted.

- Have a detailed analysis of biological finger movement considering gender and ethnicity to validate the consistency of reference input.
- Increase the similarity of the actual and designed finger motions by using simulation software to optimize the parameters.
- Implement the same system to individual fingers, but with different parameters making an arm with individually operating fingers to achieve much similar results.
- Test the designed fingers in prosthetic arms with a fair sample of individuals to test the user experience about the similarity of finger movement to the actual fingers (specially DIP and PIP joints).

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