Linkage-Based Prosthetic Fingertips: Stability Analysis

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ABSTRACT:

The purpose of this study is to analyze linkage-based prosthetic fingertips. The novel design consists of small four-bar mechanisms attached to each section of the opposing fingers replacing what would be the pulp of normal anatomical fingers. The four-bar mechanisms allow the prosthetic hand to conform to the shape of objects during grasp The goal of these prosthetic fingertips is to maximize the functionality of the hand while minimizing the number of inputs that the user has to control. This is crucial in prosthetics where the user may have limited input options, but it may also be useful in robotics.

A prosthetic hand has two functions: controlling the orientation of the artificial finger pulps and controlling their position relative to the object. We consider these two functions independently. First, we describe the small four-bar mechanisms which control the orientation of simulated pulps. The stability of the four-bar mechanisms is described as well as their advantages in contrast to a stiff-hinged single link. We then propose concepts for positioning the fingertips in two- and three-finger configurations. The focus of this paper is in the function of the four-bar fingertip mechanism; future research will address the optimal configuration of the fingertips on the hand.

The principle method used in this paper is a stability analysis via the principle of virtual work for a crossed four-bar mechanism, and, for comparison purposes, a stiff-hinged dyad. From this analysis we are able to show that four-bar fingertip mechanisms are self-stabilizing for a large range of rotation of the link on which the force is applied and a large range of directions that the force is applied. Stability is indifferent to the magnitude of the force applied to it (assuming that the force does not damage/deform the mechanism).

Keywords:
Four-bar mechanisms, stiff-hinged mechanism, prosthetic hands, fingertips, grasp stability

1. INTRODUCTION:

Our broad research objective is to improve on current prosthetic hands. Conceptually, the purpose of a hand is to place its contacting surfaces, the pulps, around an object in a way that permits the object to be grasped or manipulated. Our proposed grasping mechanism is composed of four-bar linkages attached to a prosthetic hand. In this paper, the four-bars are analyzed using virtual work to demonstrate the stability of the mechanism and to show how it differs from an alternative fingertip model, the stiff-hinged dyad.

Stability refers to the ability of a mechanism to return to and equilibrium position after undergoing a small perturbation or movement away from its equilibrium point. A common method of explaining this concept is the "ball-on-a-hill" analogy. A ball on the top of a hill may be at rest, however, a small disturbance from the top causes it to roll down the hill. On the other hand, a ball at the bottom of a valley may be at rest and a small disturbance may move the ball momentarily away from the bottom of the valley, but it soon returns. Thus, the bottom of a hill is a *stable position* because the ball returns to its equilibrium position after a small disturbance. The top of a hill is an *unstable position* because the ball does not return after a small disturbance. Stability in our context refers to the tendency of the fingertip mechanism to assume a predictable fixed position under a given loading condition and, importantly, its ability to return to that position if disturbed.

2. BACKGROUND:

In a survey of body powered prosthetic users, the top priorities of improvement were: to coordinate motions of two joints at the same time, to require less visual attention to perform certain tasks, to improve the ability to hold small and large objects better, and to improve the ability to use the hand in vigorous activities [1].

Research has developed more functional hands. Most articular segments of current prosthetic hands consist of solid linkages that have the extension and flexion movement at the joints [2-6]. This approach has been to approximate a biometic (i.e. human-like) hand, where each finger has 3 phalanges and 3 joints. Motion is restricted to the joints and not the movement of the pulps.

Researchers are also experimenting with new materials for different components. For example, the finger of the endo-skeletal prosthetic hand [7] consists of plastic phalanges. It features polyurethane foam that surrounds the endo-skeletal fingers and provides a realistic look.

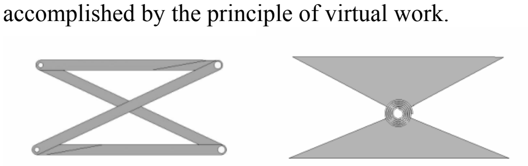
A material that can be used for the pulps is the polyurethane gel. The properties of the polyurethane gel are that it can sustain without breakage very high strain and therefore is compatible with large shape variations of the covered objects; great thermal stability; good adhesively to metallic and plastic surfaces; and it exhibits viscoelastic behavior, which is good for grasp stabilization [8].

One hand that incorporates the gel is the University of Bologna Hand, version 3. This finger articulated framework is surrounded by an external compliant cover or soft tissue that increases contact area to better adapt on objects with edges and other surface irregularities [9].

The aim of our model is simple control of the pulps. For that, analytical models of the four-bar were developed. Stability analysis of the mechanism aids the study of the ability of the hand to seize objects with a secure grasp.

3. METHODS:

We first give a brief description of equations that can be used to calculate the orientation of the links in the four-bar. Then the analysis of the crossed four-bar and the stiff hinged (Fig. 1) mechanism will be developed to find the stable region of each mechanism. This will be accomplished by the principle of virtual work.



a **b**

Figure 1: (a) Four-bar and (b) stiff-hinged mechanism

4. ANALYSIS:

The lengths of the links are L_1, L_2, L_3, and L_4, and the angles that links 2, 3 and 4 make with respect to link 1 are respectively θ_2, θ_3 and θ_4. For a particular mechanism with fixed geometry, given any of the angles, the other two can be found by solving the equations:

$$L_2 \cos\theta_2 + L_3 \cos\theta_3 = L_1 + L_4 \cos\theta_4 \quad (1)$$

$$L_2 \sin\theta_2 + L_3 \sin\theta_3 = L_4 \sin\theta_4 \quad (2)$$

For any given position of the four-bar, the method of virtual work can be used to determine the conditions in which the four-bar will be in equilibrium.

The principle of virtual work states that the net virtual work of all active forces is zero if and only if an ideal mechanical system is in equilibrium [2]. The total virtual work of the system can be written as

$$\delta W = \sum_i \vec{F}_i . \delta \vec{z}_i + \sum_j \vec{M}_j . \delta \vec{\theta}_j - \sum_k \frac{dV_k}{dq_k} \delta q_k \quad (3)$$

Where δz is the virtual displacement, $\delta\theta$ is the virtual angular displacement and q is the generalized coordinate. The analysis of the mechanism is developed using the method of virtual work [10].

The position vector of the force applied to the crossed four bar linkage (Fig. 2) is given by

$$\vec{Z} = [L_2 \cos(\theta_2) + L_3 \cos(\theta_3)]\hat{i} + [L_2 \sin(\theta_2) + L_3 \sin(\theta_3)]\hat{j} \quad (4)$$

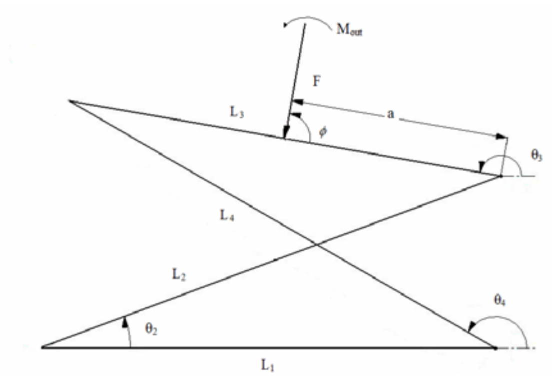


Figure 2: Model of the crossed four-bar

We apply a fictitious moment, M_{out}, as a measure of how far the four-bar is away from equilibrium given a force, F, acting in the direction, ϕ, applied at a fraction, a, of the length of link 3.

From the principle of virtual work, the moment on link 3 of the crossed four-bar mechanism required for equilibrium is found to be

$$M_{out} = F \sin\varphi (L_2 h_{23} \cos\theta_2 + aL_3 \cos\theta_3) - F \cos\varphi (L_2 h_{23} \sin\theta_2 + aL_3 \sin\theta_3) \quad (5)$$

Where:

$$h_{23} = \frac{L_3 \sin(\theta_3 - \theta_4)}{L_2 \sin(\theta_4 - \theta_2)} \quad (6)$$

h_{23} is the four-bar kinematic coefficient [10], ϕ is the angle of the force and a is the distance at which the force is applied, as shown in Figure 2.

When M_{out} =0, the crossed four bar is at equilibrium which occurs when the force angle, ϕ, satisfies

$$\tan\phi = \frac{L_2 h_{23} \sin\theta_2 + aL_3 \sin\theta_3}{L_2 h_{23} \cos\theta_2 + aL_3 \cos\theta_3} \quad (7)$$

which does not depend on the magnitude of the force, F.

Using the principle of virtual work for the stiff-hinged mechanism, as in the crossed four-bar mechanism, the moment is found to be

$$M_{out} = k(\theta_2 - \theta_{20}) - F\sin\varphi(L_2\cos\theta_2 + aL_3\cos\theta_3) + F\cos\varphi(L_2\sin\theta_2 + aL_3\sin\theta_3) \tag{8}$$

where k is the spring stiffness.

When $M_{out}=0$ in the stiff-hinged mechanism

$$\tan\phi = \frac{k(\theta_2 - \theta_{20})}{F\cos\phi(L_2\cos\theta_2 + aL_3\cos\theta_3)} + \frac{L_2\sin\theta_2 + aL_3\sin\theta_3}{L_2\cos\theta_2 + aL_3\cos\theta_3} \tag{9}$$

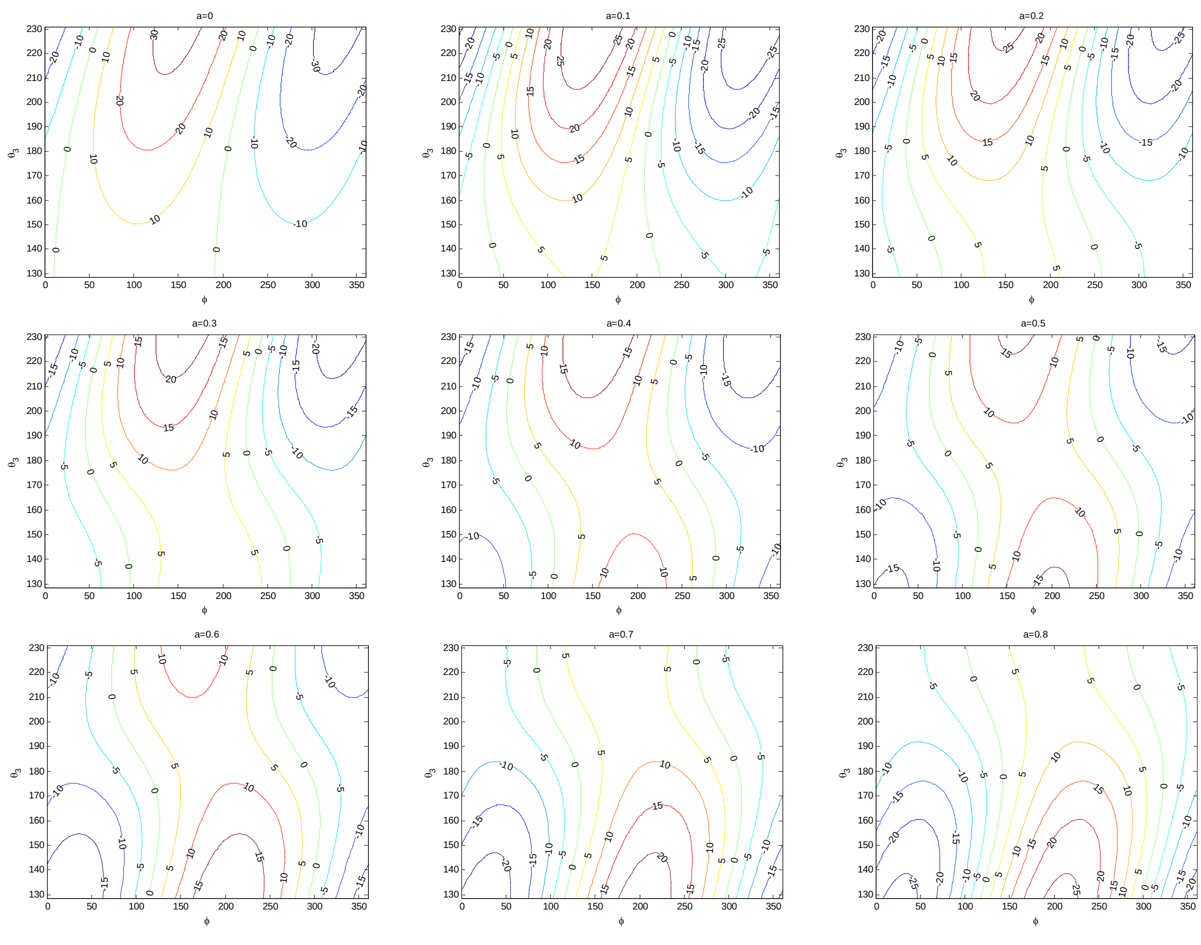
This is a definite contrast to the four-bar mechanism in that equilibrium in the stiff-hinged mechanism depends on the ratios of the spring stiffness and the applied force.

Using the moment equation, equation (5), M_{out} as a function of the angle of link 3, θ_3, and the angle force, ϕ, can be found. The equilibrium moment of the crossed bar is found for different locations of the applied force by changing the value of distance a. Figure 3 shows different plots of the angle of link 3 and the angle force for different values of the magnitude a and for the geometric parameters stated in Table 1.

Table 1 : Geometric Parameters

Set	L_1	L_2	L_3	L_4
1	1.04	1.125	1	1.125

5. RESULTS:



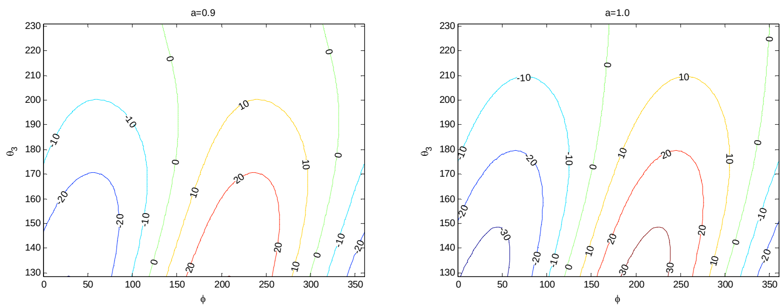


Figure 3: Instantaneous stability of crossed four bar mechanism for different values of *a*

The curves represent the moment that would be required to balance the applied force. Equilibrium curves for the different mechanisms were developed using the angle of the link, the force angle and a moment created by the force. Each equilibrium curve represents the different position on the coupler link of the four-bar (distance *a*).

Figure 4 shows the plot of the equilibrium curve when *a* =0.5, i.e. the center of link 3, in a range from 0-360 degrees. Equilibrium without an applied moment is achieved when the moment out of the mechanism is equal to zero. When the mechanism is loaded at 90^o (pulling on the mechanism) in a way that changes the orientation of link 3 from a value of 180^o (horizontal) to 200^o (slightly tipped), this corresponds to moving from point *A* to point *B* in Figure 4. At this position a moment, M_{out}, of 5 Nmm, assuming an applied force of 1 N, would be required to hold it in equilibrium. Because there is nothing in the mechanism to provide that moment the linkage will tend to continue to rotate in the positive direction and the perturbation will grow i.e. θ_3 will continue to get bigger. We say that this situation is unstable because even a very small perturbation will grow until reaches the physical limits of the mechanism's rotation.

In the other hand, when the applied force is pushing in the vertical direction, ϕ=270^o, on the center of link 3 and link 3 is perturbed from 180^o to 200^o (from *C* to *D* in Figure 4), the resulting force is -5 Nmm, indicating that this unbalanced moment will cause link 3 to rotate in the negative direction, back to its original position. Because small perturbation tend to be resisted, we say that this equilibrium position is stable when negative values of moment are above an equilibrium contour line (where M_{out}=0) and positive values of moment are below the line. An examination of the plots in Figure 3 shows that when the slope of an equilibrium contour line at a point is negative (up to the left, down to the right), the equilibrium point is stable. On the other hand, when the slope of an equilibrium contour line is positive (up to the right, down to the left) the equilibrium point is unstable.

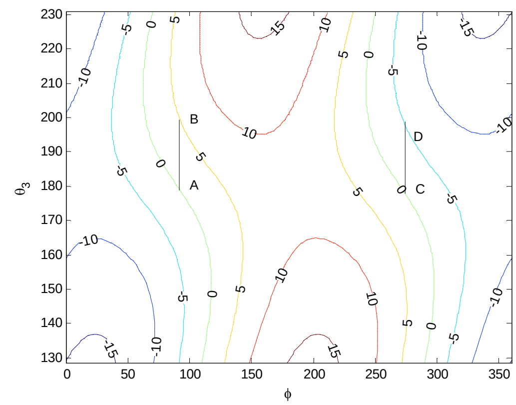


Figure 4: Stability of four bars when a=0.5

The stable region for the crossed four-bar mechanism is the shaded region in Figure 5. The advantage of this mechanism is that the magnitude of the force does not change the stability of the mechanism and it is stable over a wide range of motion and for a wide range of applied force directions and locations.

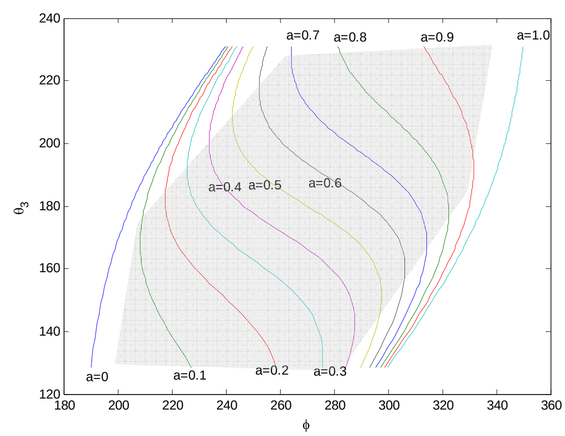


Figure 5: Stability region of four-bar mechanism

In the stiff-hinged model, the magnitude of the force plays a major role in the stability of the mechanism, the mechanism presents 3 different types of stability depending on the ratio of the spring stiffness to the force. The disadvantage of the stiff-hinged mechanism is that the degree to which it conforms to the shape of an object depends on the grasping force.

6. APPLICATION:

The human pulp is able to conform to a variety of forces. To simulate that, selection of the four-bar mechanism because they don't depend on the magnitude of the force exerted to the mechanism, it is always going to behave in the same way.

Some applications for the small four-bar mechanisms include prosthetics and robotics. Three small four-bars will be in each finger to simulate the pulps of the hand (Figures 6 and 7). With 2 fingers, the hand can grasp a variety of objects in a stable position. Planar bodies require at least 4 frictionless contacts to achieve form closure, and at least 7 frictionless contacts to achieve form closure in a spatial object [11]. The addition of a third finger helps to avoid rotation of heavy or large objects, increases the number of contacts, and gives more stability to the object grasped.

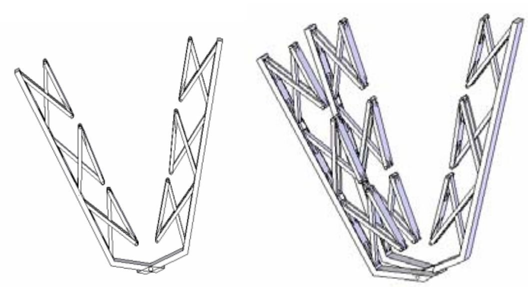
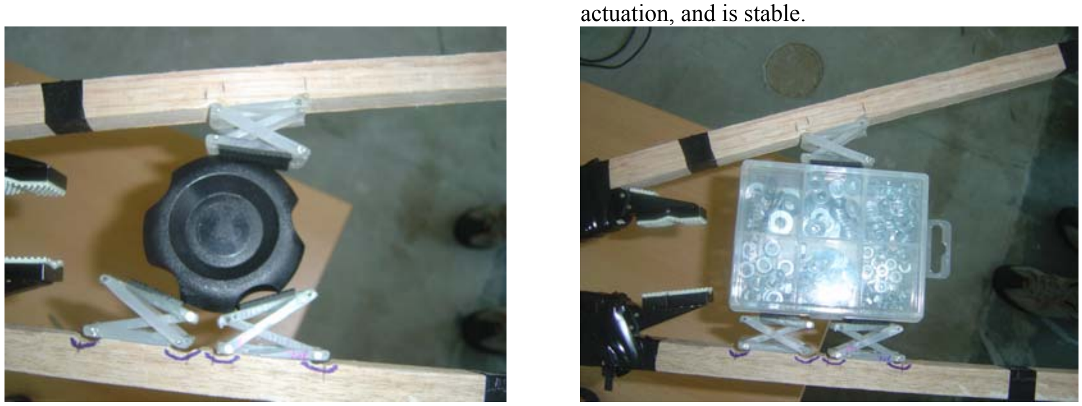


Figure 6: CAD model of four-bars in two and three fingers for a robotic gripper

A preliminary test of the fingertips was done to see the functionality of the four-bars. The four bars were made of polypropylene, and attached to a robotic gripper. In this test, the fingertips were able to grasp a variety of objects of different shapes (Figure 8). In Figure 8a, the fingertips conform to a roughly circular object and in Figure 8b, the fingertips conform to a rectangular object with flat sides. In both cases, there is a significant difference in the orientation of the wooden 'fingers' and the surface on the fingertips that contacts the grasped object. This conformity occurs passively, without actuation, and is stable.



A B

Figure 8: Preliminary test of the fingertips to hold a: a) cap and b) rectangular box

7. CONCLUSION:

The crossed four-bar mechanism fingertip is able to conform to different shapes across a broad range of angles. This mechanism is independent of the force. In a preliminary test, the fingers were able to grasp a variety of shapes. This fingertip mechanism warrants further study because of its ability to passively conform to grasped objects.

8. FUTURE WORK:

Future work includes further testing to assess whether the fingertips improve the grasping capabilities of robotic and prosthetic hands. The Southampton Hand Assessment Procedure (SHAP) test will be used to test the differences between a prosthetic device and a robotic gripper with the attached four bars and those without them. The purpose of the SHAP test is to determine the effectiveness of a terminal device and controller by focusing the evaluation in the unilateral performance of the user [12]. The SHAP consists of twenty six (26) timed tasks; twelve (12) are abstract tasks and fourteen (14) consist of activity of daily living.

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