NEW DESIGN OF SYNERGISTIC WRIST SPLINT

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ABSTRACT

Tendons are frequently injured by direct trauma. Tendon adhesions are a common factor compromising the results of tendon repair and to this day represent one of the most challenging problems in hand surgery. Use of controlled motion splints during the early stages of tendon recovery increases tendon gliding. Thus, a variety of controlled motion splints have been developed. This paper introduces a new controlled motion splint called the Synergistic Wrist Motion Splint (SWIMS). The "sequential quadratic programming method" was used to optimize Yang's synergistic model of the wrist/hand system, with the results being embodied in a practical controlled motion splint. Derivation of the model is discussed in detail. The dimensions of a patient's hand are input into a general formula to generate a specific SWIMS configuration for the patient. Five prototype SWIMS splints were produced and tested on 5 normal subjects. A three-dimensional motion analysis system was employed to measure the relative motion between the wrist and finger joints due to passive muscle tension for the prototype SWIMS splints, and the results are compared with the mathematical simulation or model.

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1. INTRODUCTION

Tendon injury is typically the result of direct trauma because the tendon is the medium that transmits force from muscle to bone during motion. Rupture and tendon adhesions are primary problems for flexor tendon recovery, and optimal postoperative treatment for obtaining good motion and strength of repaired flexor tendons has long been a clinical issue. Bunnell (1944) advised that splints should be used for

three to four weeks to protect tendons from breaking during recovery [1]. Mason and Allen (1941) [2] proved that tendons are virtually without strength during the first 5 to 7 days of recovery, and that the tensile strength improves after 14 days. It was found that early motion avoided tendon adhesions. It was also found, however, that early motion caused scar formation at both ends of the tendon. Thus early motion came to be discouraged therapeutically, a concept which limited improvements of wrist rehabilitation for many years. In 1960, Harmon and Young [3] suggested that passive motion with protective splinting would increase tendon gliding and improve functional results. Following this, the concept of "controlled motion" gradually replaced total immobilization. The efficacy of controlled motion has been supported by numerous animal studies performed over the past ten years [4,5]. Study of the effects of passive motion on subjects was conducted in a series of in vitro experiments which evaluated and

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compared the differences in tendon excursion between profundus and superficial using several mobilization techniques [6-9]. In these experiments, the concept of "the dynamic splint" was established and evaluated.

The synergistic relationship [9] between wrist joint and finger joint was studied by C. H. Yang (1993) [10]. Our group's attempt at improved splint design began with the premise that consideration of anatomical constraints and the synergistic relationship could aid optimum dynamic wrist splint design. The "sequential quadratic programming method" [14] was used to optimize Yang's model of the wrist/hand system. We found we could embody the optimized solution in a practical controlled motion splint, the Synergistic Wrist Motion Splint (SWIMS). The Type I SWIMS is a six-bar linkage mechanism, as shown in Fig. 1.

This paper will deal with the mathematical derivation of the proposed splint. Prototypes of the Type I SWIMS have been produced and tested on normal subjects. The results will be discussed below.

2. METHOD

Fig 1. Sketch of Watt's six-bar linkage and of Type I dynamic splint

The Type I SWIMS design is based on Watt's six-bar linkage mechanism [11] (Fig. 2). A structural sketch of the Type I mechanism is shown in Fig. 1.

A_0B_0 : fixed link (crank 1)

A_0A_2 : input link (crank 2)

A_1B_1D : the connecting link (crank 3)

B_0B_1 : (crank 4)

A_2C : (crank 5)

CD : (crank 6)

and we define:

A_0A_2 : the length from Wrist joint to metatarsal phalangel (MP) joint

A_2C : the length from MP joint to proximal interphalangel (PIP) joint

CD : the length from PIP joint to PIP joint

Based on the theory of optimization, we can find the upper and lower bounds of the crank angles and lengths. To do so, first, we set the variables x_1, x_2, x_3 and x_4 as the lengths of crank r_1, r_3, r_4 and r_5 respectively. The curve generated by the possible locations of point D (the tip of the finger, henceforth TIP) is the desired solution. The coordinant points for possible D are thus (Eqs. 1-2):

$$f_{Dx} = r_1 \cos \theta_1 + r_4 \cos \theta_4 + r_5 \cos \theta_5 \quad (1)$$

$$f_{Dy} = r_1 \sin \theta_1 + r_4 \sin \theta_4 + r_5 \sin \theta_5 \quad (2)$$

Because the six-bar linkage is a closed loop, the set of possible coordinant points for the position of TIP is (Eqs. 3-4):

$$f_{TIPx} = r_2 \cos \theta_2 + r_6 \cos \theta_6 + r_7 \cos \theta_7 \quad (3)$$

$$f_{TIpy} = r_2 \sin \theta_2 + r_6 \sin \theta_6 + r_7 \sin \theta_7 \quad (4)$$

Based on this, we can find the objective function,

Fig 2. Structural sketch of Watt's six-bar linkage mechanism

constraint function and the variable of the mechanism by solving these equations via optimization.

$f(X)$ (objective function) (Eqs. 5):

$$f(X) = (f_{Dx} - f_{TPx})^2 + (f_{Dy} - f_{TPy})^2 \quad (5)$$

$g_i(X)$ (constraint function) (Eqs. 6-17):

$$g_1(X) = -r_1 \leq 0 \quad (6)$$

$$g_2(X) = -r_3 \leq 0 \quad (7)$$

$$g_3(X) = -r_4 \leq 0 \quad (8)$$

$$g_4(X) = -r_5 \leq 0 \quad (9)$$

$$g_5(X) = -\theta_3 \leq 0 \quad (10)$$

$$g_6(X) = -\theta_4 \leq 0 \quad (11)$$

$$g_7(X) = \theta_3 - \pi/2 \leq 0 \quad (12)$$

$$g_8(X) = \theta_4 - 3\pi/2 \leq 0 \quad (13)$$

$$g_9(X) = r_1 \cos \theta_1 + r_4 \cos \theta_4 - r_3 \cos \theta_3 - r_{21} \cos \theta_2 = 0 \quad (14)$$

$$g_{10}(X) = r_1 \sin \theta_1 + r_4 \sin \theta_4 - r_3 \sin \theta_3 - r_{21} \sin \theta_2 = 0 \quad (15)$$

$$g_{11}(X) = r_{22} \cos \theta_2 + r_6 \cos \theta_6 - r_7 \cos \theta_7 - r_3 \cos \theta_3 - r_5 \cos \theta_5 = 0 \quad (16)$$

$$g_{12}(X) = r_{22} \sin \theta_2 + r_6 \sin \theta_6 - r_7 \sin \theta_7 - r_3 \sin \theta_3 - r_5 \sin \theta_5 = 0 \quad (17)$$

The variable X and its upper/lower bounds are (Eqs. 18-21):

$$0 \text{ cm} \leq X_1 \leq 20 \text{ cm} \quad (18)$$

$$0 \text{ cm} \leq X_2 \leq 20 \text{ cm} \quad (19)$$

$$0 \text{ cm} \leq X_3 \leq 20 \text{ cm} \quad (20)$$

$$0 \text{ cm} \leq X_4 \leq 20 \text{ cm} \quad (21)$$

In practical application, the patient's X values are input to the above equations. The "sequential quadratic

programming method" [10] is used to obtain the optimum solutions, and the results are used to fabricate a customized SWIMS splint for the patient. Five experimental Type I SWIMS splints were constructed. The actual joint angles generated by the prototypes will be compared with the analytical solutions in a following section.

3. EXPERIMENT

Five normal subjects, male, average age 25, with no physical abnormalities, were recruited from the students at National Cheng Kung University Medical Center. From their physical measurements, five prototype SWIMS Type I dynamic splints were fabricated, one for each subject, each one custom-made for one subject.

Each subject wore his splint during experiments wherein the relative joint positions of the hand and wrist were measured by a six-camera three-dimensional motion analysis system. Passive external reflective markers were placed on the dorsal surface of the subject's hand. The positions of the markers are shown in Fig. 3. During the experiment, the subject's hand is relaxed and only the wrist has flexion and extension. The experimental motion cycle is defined as follows: when the wrist flexes, the fingers extend, and when the wrist extends, the fingers flex. For kinetic analysis, each finger segment is assumed to be a rigid body, the PIP joint is assumed to be a hinge joint, and only flexion and extension are allowed. The MP joint and wrist joint are simplified into a single hinge joint. The mathematical models of the instantaneous angles for the PIP joint, MP joint and wrist joint are:

1. PIP joint angle (Eqs. 22):

Fig 3. Marker set for hand motion analysis and picture of Wrist, MP and PIP joints.

Table 1: Finger and palm length of subjects

	r_1	r_3	r_4	r_5	θ_1	β
subject 1	3.5277 cm	6.4422 cm	5.2604 cm	15.2355 cm	$\frac{\pi}{3}$	$-\frac{\pi}{15}$
subject 2	2.8658 cm	4.7563 cm	7.6272 cm	14.8900 cm	$\frac{10\pi}{21}$	$\frac{\pi}{60}$
subject 3	3.0976 cm	5.2120 cm	6.8117 cm	14.1473 cm	$\frac{100\pi}{245}$	0
subject 4	2.4235 cm	4.6691 cm	6.1470 cm	14.0208 cm	$\frac{10\pi}{26}$	$-\frac{\pi}{15}$
subject 5	3.2457 cm	5.3707 cm	7.4425 cm	14.6304 cm	$\frac{10\pi}{22}$	$\frac{\pi}{60}$

Table 2: Result under control five points

	r_1	r_3	r_4	r_5	θ_1	β
subject 1	3.5277 cm	6.4422 cm	5.2604 cm	15.2355 cm	$\frac{\pi}{3}$	$-\frac{\pi}{15}$
subject 2	2.8658 cm	4.7563 cm	7.6272 cm	14.8900 cm	$\frac{10\pi}{21}$	$\frac{\pi}{60}$
subject 3	3.0976 cm	5.2120 cm	6.8117 cm	14.1473 cm	$\frac{100\pi}{245}$	0
subject 4	2.4235 cm	4.6691 cm	6.1470 cm	14.0208 cm	$\frac{10\pi}{26}$	$-\frac{\pi}{15}$
subject 5	3.2457 cm	5.3707 cm	7.4425 cm	14.6304 cm	$\frac{10\pi}{22}$	$\frac{\pi}{60}$

Table 3: Results using eight control points

	r_1	r_3	r_4	r_5	θ_1	β
subject 1	3.2585 cm	6.0350 cm	5.4366 cm	14.8689 cm	$\frac{\pi}{3}$	$-\frac{\pi}{15}$
subject 2	3.2135 cm	5.4197 cm	8.0027 cm	15.5421 cm	$\frac{10\pi}{21}$	$\frac{\pi}{30}$
subject 3	3.0001 cm	5.1472 cm	6.9006 cm	14.0995 cm	$\frac{10\pi}{25}$	0
subject 4	3.3790 cm	5.9707 cm	6.6944 cm	15.4448 cm	$\frac{10\pi}{28}$	$-\frac{\pi}{30}$
subject 5	2.9025 cm	4.8813 cm	7.4454 cm	14.1672 cm	$\frac{10\pi}{22}$	$\frac{\pi}{30}$

$$\theta_{PIP} = \cos^{-1} \left(\frac{\vec{P_1P_2} \cdot \vec{P_2P_3}}{\|\vec{P_1P_2}\| \|\vec{P_2P_3}\|} \right)$$

2. MP joint angle (Eqs. 23):

(22)

$$\theta_{MP} = \cos^{-1} \left(\frac{\vec{P_2P_3} \cdot \vec{P_3P_4}}{\|\vec{P_2P_3}\| \|\vec{P_3P_4}\|} \right)$$

3. wrist joint angle (Eqs. 24):

(23)

Fig. 4: Motion of D point (with five control points)

Fig. 5 : Motion of D point (with eight control points)

$$\theta_{Wrist} = \cos^{-1} \left(\frac{\begin{matrix} \vec{P_3P_4} \cdot \vec{P_5P_6} \\ |\vec{P_3P_4}| |\vec{P_5P_6}| \end{matrix}}{\begin{matrix} \vec{P_3P_4} \cdot \vec{P_5P_6} \\ |\vec{P_3P_4}| |\vec{P_5P_6}| \end{matrix}} \right) \quad (24)$$

4. RESULTS

The measurements for each segment of the subject's index finger (wrist joint to MP joint, MP joint to PIP joint and PIP joint to TIP) are used with optimization methods to determine suitable crank lengths r_1, r_3, r_4, r_5 and angles θ_1 and β for splint manufacture. The motion curves predicted numerically for point D (TIP) are then compared with the motion curves observed by the six-camera motion system for Type I

SWIMS. Table 1 shows the finger segment lengths. Tables 2 & 3 show the optimized dimensions, Table 2 using 5 control points, Table 3 using 8 control points. The results in Table 2 are presented graphically in Fig. 4 as the curve composed of zeros, showing the numerically generated motion of point D. Fig. 6 also shows, as the curve composed of asterisks, the TIP curve of the hand as measured by the six-camera system. Similar data is shown in Table 3 and Fig. 5 for the eight-control-point results. As can be seen, both the 5 and 8 point simulations provide approximately equal results. Thus, 5-control-point optimization may be used for splint design.

5. DISCUSSIONS AND CONCLUSION

It is desired to fit the orbit of point D to the orbit

Fig. 6: Lateral view of Type II dynamic splint

Fig. 7: Upper view of Type II dynamic splint

of TIP for the range of natural wrist motion by optimization of input values for angles θ_1 and β and ratios r_{21} and r_{22} . For most of the orbit of the Type I SWIMS prototype, D and TIP curves were similar, with moderately increased differences at the beginning and end of the curves. Thus, it can be seen that Watt's six-bar linkage mechanism can be used to successfully simulate wrist motion, and, further, that Type I SWIMS would seem useful in providing optimal dynamic splinting for hand surgery patients. Final confirmation of Type I SWIMS, however, awaits clinical testing.

Our main discovers are listed as below :

1. Watt's six-bar linkage mechanism provides a useful basis for design of a dynamic wrist splint.

2. Comparison of the experimentally-observed motion of a Type I SWIMS prototype with the numerical model shows good agreement between obtained and desired results for wrist flexion and extension less than

40 degrees.

3. It was found that the results for both 5 and 8 points simulations provided approximately equal results. Thus, 5-control-point optimization may be used for splint design.

6. FUTURE

Clinical testing of the Type I SWIMS is of interest. A pulley-based Type II SWIMS design is in progress (Fig.6,7). We are developing a general model for the relationship between each segment of the fingers. From this, it would be possible to determine the crank length needed to fabricate the dynamic splint simply and directly from a patient's finger length.

Because the lengths of linkages 5 and 6 are equal to the lengths from MP joint to PIP joint and from PIP joint to TIP joint, respectively, it may be possible to

simplify the model into four-bar linkage mechanism. However, the motion center axis of each segment of the palm must be measured before analyzing this mechanism.

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