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CONNECTING THE WRIST TO THE HAND: HOW DOES THE DESIGN OF THE WRIST INFLUENCE MOMENT ARMS OF WRIST AND HAND MUSCLES?

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INTRODUCTION

The wrist is a complicated joint that implant technology has failed to effectively replicate [1]. As a result, salvage procedures are used to treat wrist osteoarthritis, unlike the hip or knee where joint replacement is the gold standard. Salvage procedures successfully relieve pain by sacrificing the complex design of the wrist, but have the unintended consequence of causing long-term impairments in hand function [2, 3]. Understanding the mechanism by which surgically simplified wrists impact hand function could elucidate the complexity required in artificial wrists and aid the development of surgical techniques that better replicate nonimpaired wrist and hand function.

One mechanism by which the wrist impacts the hand is through muscle actions. There are more than fifteen muscles and muscle compartments that originate in the forearm, cross the wrist, and power the hand. Because wrist posture can be used to modulate the torque-generating parameters of these muscles, wrist posture influences hand strength [4] and plays a critical role in daily tasks involving the hand [5]. Ideally, surgically simplifying the wrist would preserve this complex design. Yet, to what extent salvage procedures alter the actions of wrist and hand muscles is unknown.

As a step toward understanding the relationship between the wrist's design, muscle actions, and hand function, we examined muscle moment arms following two common salvage procedures: scaphoid-excision four-corner fusion (SE4CF) and proximal row carpectomy (PRC). Moment arm is the geometric factor that transforms muscle force into joint torque. Therefore, it provides insight into muscle torque-generating capacity, a critical factor when examining muscles. We hypothesized that moment arms would change in divergent ways following SE4CF and PRC because these procedures alter the geometry of the wrist differently (Fig. 1). We measured moment arms of the primary wrist and extrinsic thumb muscles to investigate how simplifying the wrist affects not only wrist muscles, but also the muscles crossing the wrist and powering the hand.

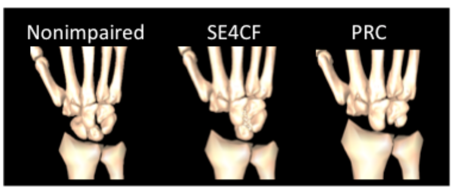

Figure 1: Nonimpaired and surgically salvaged wrists.

METHODS

Wrist muscle moment arms were measured in 8 cadaveric specimens (4 female; avg. age 62.3 ± 8.9) using the tendon excursion method [6]. In each specimen, data were collected sequentially for three conditions: nonimpaired, SE4CF, and PRC. To simulate SE4CF, the scaphoid was excised and four carpal bones (lunate, capitate, hamate, and triquetrum) were fused using k-wires. Fusion, scaphoid excision, and neutral alignment of the lunate were confirmed using fluoroscopy. To simulate PRC, the k-wires were removed and the remaining proximal carpal bones (lunate and triquetrum) were excised. The finger extensor tendons and soft tissues were imbricated to establish an interface between radius and capitate. Neutral alignment of radius and capitate was confirmed using fluoroscopy.

Tendon excursion and joint angle data were collected during passive, planar wrist motion for two degrees of freedom: flexion-extension and deviation. In each specimen and for each condition, at least 30 trials were recorded for each degree of freedom. Tendon excursions were simultaneously recorded from the five primary wrist muscles (FCR, FCU, ECRL, ECRB, ECU) and four extrinsic thumb muscles (FPL, EPL, EPB, APL) using potentiometers (Model 3543s, Bourns Inc.). Data was not recorded from the EPB in two specimens due to this muscle not being present. Joint angles were calculated as the angle between the long axes of the third metacarpal and radius. Locations of the radius and third metacarpal were measured by a motion capture system (Optotrak Certus, Northern Digital Inc.). The collected data was digitally sampled to provide joint angles and their corresponding tendon excursions at 0.5 degree increments.

Moment arms (defined as the change in tendon excursion divided by the change in joint angle) were calculated using numerical differentiation. To smooth data, fourth order polynomials were fit to each trial. The flexion-extension moment arm of the EPB following PRC was excluded from analysis due to the paucity of high quality trials.

Statistically significant differences between nonimpaired, PRC, and SE4CF moment arms were determined using mixed effects models, including condition and joint angle as fixed factors and specimen as a random factor. A significance level of $p<0.05$ was used for all tests. When the F-test of the ANOVA was significant, multiple comparisons with a Tukey correction were used.

RESULTS AND DISCUSSION

The data indicate that PRC primarily alters flexion-extension moment arms, while SE4CF primarily alters deviation moment arms (Table 1). When comparing the nonimpaired and surgically altered flexion-extension moment arms, 5 muscles demonstrated significant changes following PRC, but only 1 following SE4CF. In contrast, when comparing deviation moment arms, 7 muscles demonstrated significant changes following SE4CF, but only 2 following PRC. Additionally, significant differences in moment arms were observed following at least one of the two salvage procedures for all four extrinsic thumb muscles.

Altering the moment arms of different degrees of freedom suggests that the force-generating requirements of the wrist muscles will be different following PRC and SE4CF. For example, PRC substantially alters the ratio between the moment arms of the primary wrist extensors and flexors (Fig. 2). Unlike the nonimpaired and SE4CF wrists, in which the sum of the wrist extensor moment arms is approximately equal to the sum of the flexor moment arms for the full range of motion, the PRC wrist has relatively smaller wrist extension moment arms in extended postures (cf. red curve, Fig. 2, ratio < 1 for negative angles). This suggests that, even without considering the muscle force-generating capacity, the net mechanical actions of the flexors overpower those of the extensors during wrist extension following PRC. Therefore, the wrist extensors will have to generate more force to maintain wrist extension (or the flexors have to generate less) following PRC. In contrast, SE4CF alters the ratio between the moment arms of the primary radial and ulnar deviators (data not shown), suggesting that following SE4CF wrist muscles have altered force requirements during deviation. Thus, the changes in force-generating requirements reflect the primary changes in moment arms and suggest that different forces are needed to maintain equivalent postures in the nonimpaired, SE4CF, and PRC wrists. The need to adjust for these altered biomechanical requirements likely contributes to post-operative functional impairments.

The significant changes in the moment arms of the extrinsic thumb muscles indicate that PRC and SE4CF alter muscles that directly impact hand function. However, the conclusions we can draw regarding these changes are limited. We know the extrinsic thumb muscles are critical for producing endpoint force at the thumb-tip [7], yet to what extent changing the wrist moment arms of these muscles influence endpoint force production is unknown. One reason for this lack of knowledge is because data on extrinsic thumb muscles is extremely limited. To our knowledge, only two studies (including this one) have examined the nonimpaired wrist moment arms of all four extrinsic thumb muscles [8]. By examining both the nonimpaired wrist and the wrist following surgeries that negatively impact hand function, this study provides novel data and is the first step to understanding how moment arms of muscles crossing the wrist impact hand function.

CONCLUSIONS

This study demonstrates that surgical salvage procedures significantly alter moment arms of both the primary wrist and extrinsic thumb muscles. Therefore, surgically simplifying only the bone geometry of the wrist impacts the mechanical actions of the muscles controlling not only the wrist, but also the hand.

Table 1. Changes in Muscle Moment Arm*

Muscles		Flexion-Extension Moment Arm		Deviation Moment Arm	
		SE4CF	**PRC**	**SE4CF**	**PRC**
Wrist	**FCR**	-	X	X	-
	FCU	-	-	-	-
	ECRB	-	X	X	-
	ECRL	-	-	X	-
	ECU	-	X	X	X
Thumb	**FPL**	-	X	X	-
	EPL	X	X	-	-
	APL	-	-	X	-
	EPB	-		X	X

*Differences between data from the nonimpaired wrist and the indicated surgery are reported. Significant differences denoted by X. Excluded data denoted by gray shading.

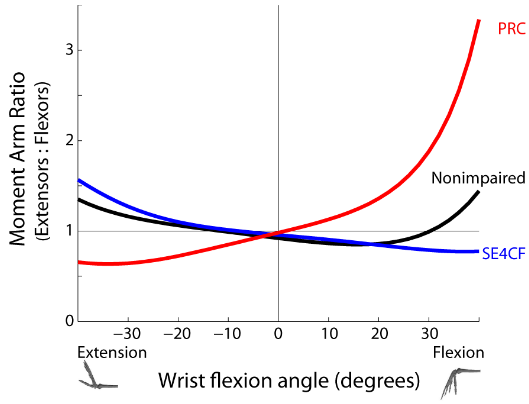

Figure 2: Ratio of moment arms between the primary wrist extensors (ECRL, ECRB, ECU) and flexors (FCR, FCU) for the nonimpaired and salvaged wrists. Ratio calculated by dividing the sum of the extensor moment arms by the sum of the flexor moment arms. Ratio equal to one means the mechanical advantage of the extensors and flexors is equal.

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REFERENCES

1. Levadoux M & Legre R, *J Hand Surg* **28**:405-13, 2003.
2. Bain G & Watts A, *J Hand Surg Am.* **35**:719-25, 2010.
3. Richou J, et al. *Chir Main.* **29**:10-15, 2010.
4. O'Driscoll S, et al. *J Hand Surg Am.* **17**:169-177, 1992.
5. Adams B, et al. *J Hand Surg Am.* **28**:898-903, 2003.
6. An K, et al. *J Biomech.* **16**:419-425, 1983.
7. Wohlman S & Murray W *J Biomech.* doi: 10.1016/ j.jbiomech.2012.10.044, 2013.
8. Brand P & Hollister A. *Clinical Mechanics of the Hand,* 3rd ed. 1999.