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의학박사 학위논문

Biomechanical Analyses of the Quadriga Phenomenon of the Fifth Flexor Digitorum Profundus Tendon: A Cadaveric Study

제5수지 심수지 굴곡건에 발생하는 사두마차 현상의 생역학적 분석: 사체 실험

2013년 2월

서울대학교 대학원

의학과 정형외과학 전공

이 혁 진

A thesis of the Degree of Doctor of Philosophy

제 5 수지 심수지 굴곡건에 발생하는 사두마차 현상의 생역학적 분석: 사체 실험

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February 2013

The Department of Orthopedic Surgery

Seoul National University

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Biomechanical Analyses of the Quadriga Phenomenon of the Fifth Flexor Digitorum Profundus Tendon: A Cadaveric Study

by

Hyuk Jin Lee

A thesis submitted to the Department of Orthopedic Surgery in partial fulfillment of the requirement of the Degree of Doctor of Philosophy in Medicine at Seoul National University College of Medicine

December 2012

Approved by Thesis Committee:

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사두마차 현상의 생역학적 분석: 사체 실험

학위구분: **석사 □ · 박사 ■**
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제 출 일: 2013 년 2 월 4 일

서울대학교총장 귀하

ABSTRACT

Introduction: The quadriga phenomenon is a decrease in flexion of a normal finger after the proximal excursion of the flexor digitorum profundus (FDP) tendon of an adjacent injured finger has been limited. This phenomenon may reduce the normal physiological functions. The purpose of this study was to analyze changes in biomechanical parameters associated with normal and FDP tendon shortened fingers using a cadaver model to verify the quadriga phenomenon when the fifth FDP tendon was shortened incrementally, and to suggest the necessary surgical restoration of tendon length that will restore adequate function. especially in regards of fifth FDP tendon-injured patients.

Methods: Ten fresh-frozen cadaveric hands were used for the experiments. After preparation of the FDP and extensor tendons, the cadaveric hands were fixed on a frame. The biomechanical parameters that were measured were the force to make the fifth finger flex fully, the excursion of the fourth FDP tendons, and the flexion angles of distal interphalangeal (DIP) joint, proximal interphalangeal (PIP) joint, and metacarpophalangeal (MCP) joint of the fourth and fifth fingers. The fifth FDP tendon was then incised and shortened by 5mm at a level in zone 3 and repaired with a modified Kessler method. The aforementioned biomechanical parameters were then re-measured. Subsequently, using similar methods, the fifth FDP tendon was shortened by a total 10 mm and 15 mm and the biomechanical parameters then re-measured.

Results: The reduction in the total range of motion (ROM) of the fourth finger was dependent on the amount of shortening of the fifth FDP tendon. The flexion angles of the DIP, PIP and MCP joints of the fourth finger were increased when the fifth FDP tendon was shortened 5 mm, 10 mm, and 15 mm, respectively. The extension lag of the DIP, PIP and MCP joint angles of fourth finger varied linearly with shortening of fifth FDP tendon. The regression equation for extension lag of the DIP joint was Y = -2.17X + 60.0 ($R^2 = 0.616$, $p < 0.001$), where Y is the amount of extension lag of the DIP joint and X is the amount of shortening (mm) of the fifth FDP tendon. Similarly, the regression equation for the PIP joint was Y = -1.67X + 81.68 ($R^2 = 0.392$, $p < 0.001$), and Y = -1.25X + 79.65 for the MCP joint ($R^2 = 0.548$, $p < 0.001$). The regression equation for the change of excursion of the fourth FDP tendon after shortening of the fifth FDP tendon was Y = - 0.926X + 32.52 ($R^2 = 0.505$, $p < 0.001$), where Y is the change in excursion of the fourth FDP tendon and X is the same as described above.

Conclusion: This study successfully demonstrated the quadriga phenomenon in a cadaveric model with fifth FDP tendon shortening model. Our results indicate that after fifth FDP tendon injury, it is important to restore the tendon to its original length accurately to ensure adequate function of adjacent fingers.

Keywords: Quadriga phenomenon, Extension lag, Tendon excursion, Cadaveric study

Student number: **2011-30572**

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INTRODUCTION

The quadriga, or profundus tendon blockage, phenomenon manifests as a decrease in flexion of a normal finger after the proximal excursion of the flexor digitorum profundus (FDP) tendon of an adjacent injured digit has been limited. Bunnell[1] first described the phenomenon, and Verdan[15] used the term 'quadriga'. The term quadriga is derived from the Roman four-horse chariots. Verdan's explanation of the phenomenon related to an effect of the common muscular body upon the flexor tendons when there was a functional limitation of an individual tendon. The muscular body could act efficiently only if the gliding amplitude of each of the four tendinous reins was normal[15].

The quadriga phenomenon may occur due to a variety of conditions, such as when one FDP tendon is advanced too far distally in a reattachment procedure in zone 1. Other causes include a tendon graft that is too short, a distal finger amputation in which the flexor tendon is sutured over the tip to the extensor tendon, or an amputation in which the FDP tendon adheres to the proximal phalanx[6]. It occurs most commonly when full proximal excursion of one of the FDP tendons is prevented by finger stiffness or adhesion[7].

In this condition, the profundus tendon of the affected finger can block the excursion of the profundus tendon of other fingers. The weakness of the adjacent fingers as a result of their restricted finger flexion may cause a loss of grip strength. Horton et al.[7] quantified this effect by providing a block to flexion for one finger and observing the effect on the strengths of the other three fingers of the same hand.

In anatomical term, the quadriga phenomenon is frequently attributed to the common muscle belly of the FDP. A common muscle origin arises from the flexor aspect of the ulna and the interosseous membrane and then separates into two muscle bellies. The larger ulnar mass moves the ulnar three fingers, and the smaller radial part the second finger. Seven to twelve tendon units that are clearly linked together arise from the ulnar muscle belly. Distally these units form the three definitive tendons for the third, fourth and fifth finger. These tendons are also joined at the base of the palm by the origins of the third and fourth lumbrical muscles. The radial muscle belly provides a single tendon for the second finger[4], thus motion of the FDP tendon to the second finer is independent of that of the other FDP tendons.

Recently, Segal et al.[14] reported that the FDP muscle belly was divided into two or more partitions by a nerve innervation pattern. The authors showed that the anterior interosseous nerve of the median nerve innervates all of the muscle fibers to second and third FDP tendons, as well as some of the muscle fibers to fourth FDP tendons, whereas branches of the ulnar nerve innervates all of the muscle fibers to the fourth and fifth FDP tendons. They also showed that the muscle fibers inserting into the fourth and fifth FDP tendon were a single partition.

Reilly and Schieber[11] showed the four subdivisions were activated to the greatest extent during individuated flexion of the second, third, fourth and fifth fingers in their electromyographic study. They suggested four core regions each act selectively on a single finger and other less-selective regions were active during flexion of adjacent fingers as a result of their biomechanical connections and overlapping territories.

In the present study, it was assumed that the second FDP tendon moves independently of other FDP tendons and the motion of third FDP tendon has greater independence of motion than the fourth and fifth FDP tendons.

Clinically, less satisfactory results have been noted for fifth FDP tendon injuries than for the other digits[2,3,5,10]. The fifth finger is more flexed in the neutral position in the hand, hence the fifth finger appears to be more severely contracted. Further, the comparative weakness of the extensor compared to the flexor tendon power may cause a more contracted and stiffened fifth finger. Also, the smaller size of the fifth FDP tendon might lead to re-rupture after repair. Repeated repair of the tendon might cause FDP tendon shortening. Given these findings, the quadriga phenomenon can be more easily produced with shortening of the fifth FDP tendon.

Thus far, the quadriga phenomenon has been described based on clinical findings. For the present study, the excursion of fifth FDP tendon was reduced in a cadaver model to cause the quadriga phenomenon in the fourth finger.

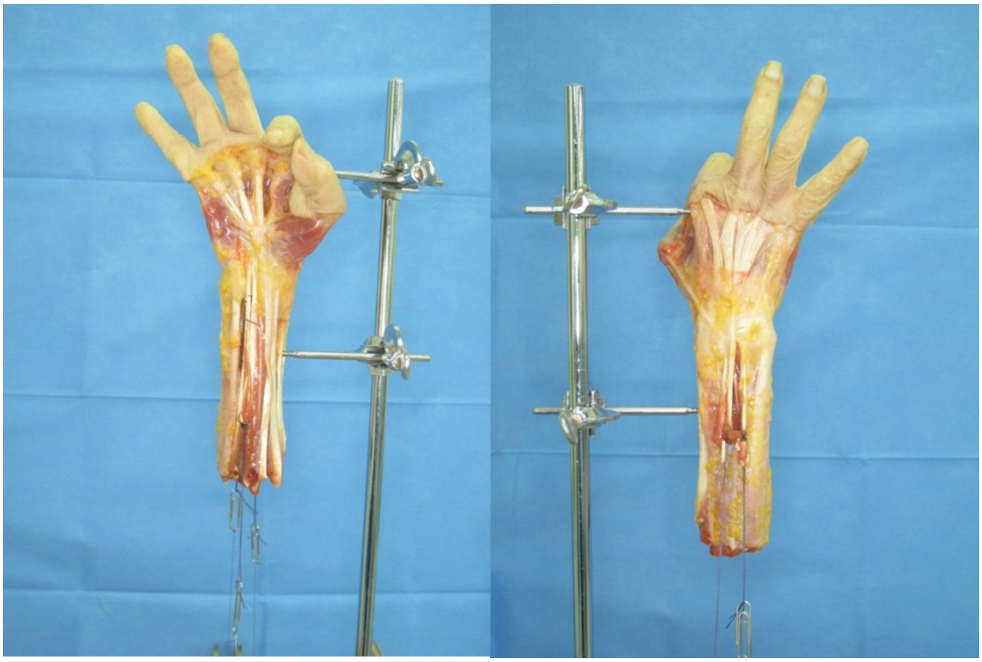
The purpose of this study was to analyze changes in biomechanical parameters associated with normal and FDP tendon-shortened fingers, using a cadaver model to verify the quadriga phenomenon when the fifth FDP tendon was shortened incrementally, and to suggest the necessary surgical restoration of tendon length that will restore adequate function, especially in regards to fifth FDP tendon-injured patients.

MATERIALS AND METHODS

Ten fresh cadaveric hands were used for the experiments. There were two males and three females with an average age of 83 (range, 75 to 97) years. All hands were severed at the mid-elbow level preserving the origin of the FDP and, extrinsic flexors and extensors, all of which demonstrated a full range of motion (ROM) at all metacarpophalangeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints.

All the extrinsic muscle tendons, including flexor digitorum superficialis (FDS), FDP, extensor digitorum communis (EDC), and extensor indicis proprius (EIP) were dissected without any injuries. We identified the origin of the FDP common muscle bellies. Among these muscle bellies, we incised the muscle belly of the fourth and fifth FDP at the origin and tied them with 1-0 polysorb™ suture (Covidien, Inc., Norwalk, CT). Also, the fourth and fifth EDC tendons were dissected and incised at the musculotendinous junction. These tendons were also tied with 1-0 polysorb™ suture (Covidien, Inc., Norwalk, CT). A loop to hold the weights was made at the end of each suture. We inserted 4mm half pins at the metacarpal neck and the distal one-third point of the radius on the radial side, so as not to transfix or compress any flexor or extensor tendons. We fixed two half pins to the clamps of the frame that was custom made for these experiments (Fig. 1).

Each thread, some of which were tied in loops, was connected to wires. The other end of the wire was connected to weights and tension was applied to the tendons through a pulley system (Fig. 2). The initial tension applied to the fourth and fifth extensor tendons was such to produce a neutral joint position for the MCP, PIP and DIP joints (Fig. 3).



Half pins were inserted at the metacarpal neck and the distal one-third point of the radius on the radial side. These half pins were connected to the clamps of the frame.

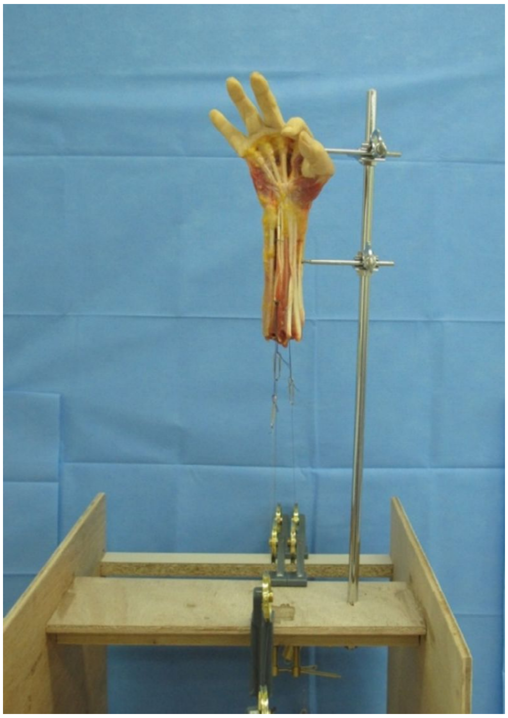


Figure 2. Preparation of cadaveric forearm to the frame (2)

Each thread and loop of thread was connected to the 29 gauge wires and weights were connected to the other end of the wires. The wires connected to the fourth and fifth FDP tendons were set on pulleys on the volar side of the frame and the fourth and fifth extensor tendons were set on pulleys on the dorsal side of the frame.

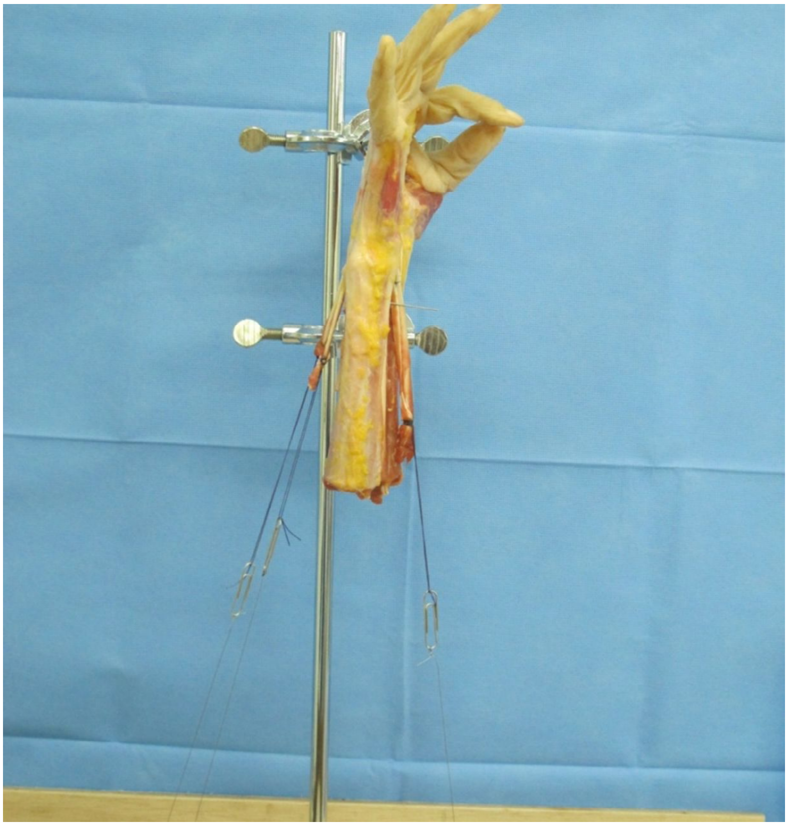


Figure 3. **Tensioning to extensor tendon**

The initial tension applied to extensor tendon in the fourth and fifth finger.

The force to make the fifth finger flex fully was measured with a force gauge (Basic Force Gauge, Mecmesin, UK), repeated three times (Fig. 4). The excursion of the fourth FDP tendon between two reference points was measured with a vernier caliper. One of the reference points was located in the fourth FDP tendon using a suture and the other point was located in the radius using a K-wire. The excursion of the fourth finger from full extension to full flexion was measured (Fig. 5). The DIP, PIP and MCP joint flexion angles were measured with a goniometer (Fig. 6).

The fifth FDP tendon was shortened by 5 mm at a level in zone 3. The incised tendon was repaired end-to-end with a modified Kessler method using 3-0 Prolene (Ethicon, Johnson and Johnson, US) (Fig. 7). The prepared cadaveric forearm was mounted to the custom frame, and the average force that needed to cause full flexion before shortening was applied to the fourth and fifth FDP tendons. We measured the excursion of the fourth FDP tendon and the fourth and fifth finger flexion angles at the DIP, PIP, and MCP joints.

Using the same technique, the fifth FDP tendon was sequentially shortened by a total of 10 mm and then 15 mm and the aforementioned parameters were re-measured.

The statistical differences between the angles of each joint were calculated using Kruskal-Wallis test using SPSS ver.18.0 (SPSS Inc., Chicago, IL). Simple linear regression analyses were performed to assess the relationship between the angle of each joint, the excursion of the fourth FDP tendon and shortening of the fifth FDP tendon. We considered p-values < 0.05 to be statistically significant.

Figure 4. **Measuring of the tension**

The force to make the fifth finger flexed fully was measured with a force.

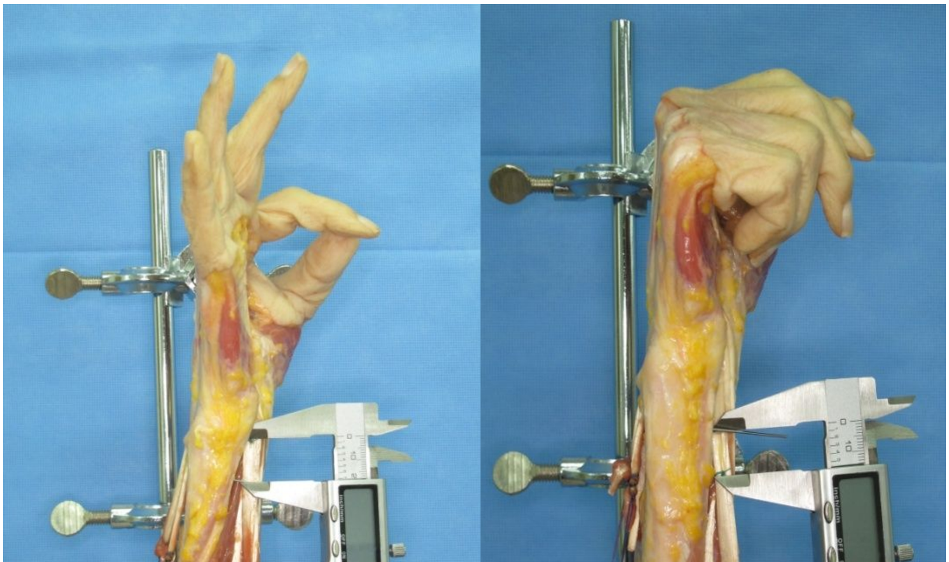
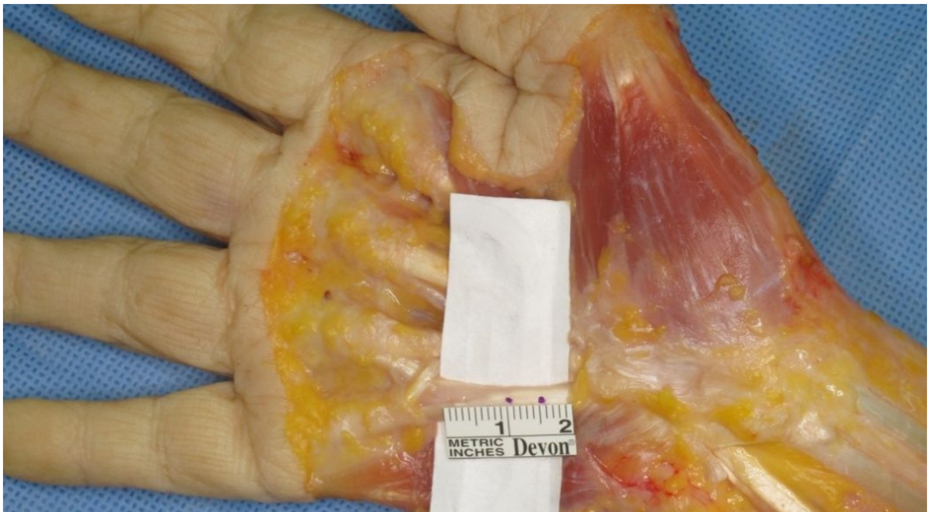


Figure 5. **Measuring of the excursion**

We measured the excursion of the fourth FDP from extension to flexion.

Figure 6. **Measuring of the angles**

We measured the DIP, PIP and MCP joints flexion angles.



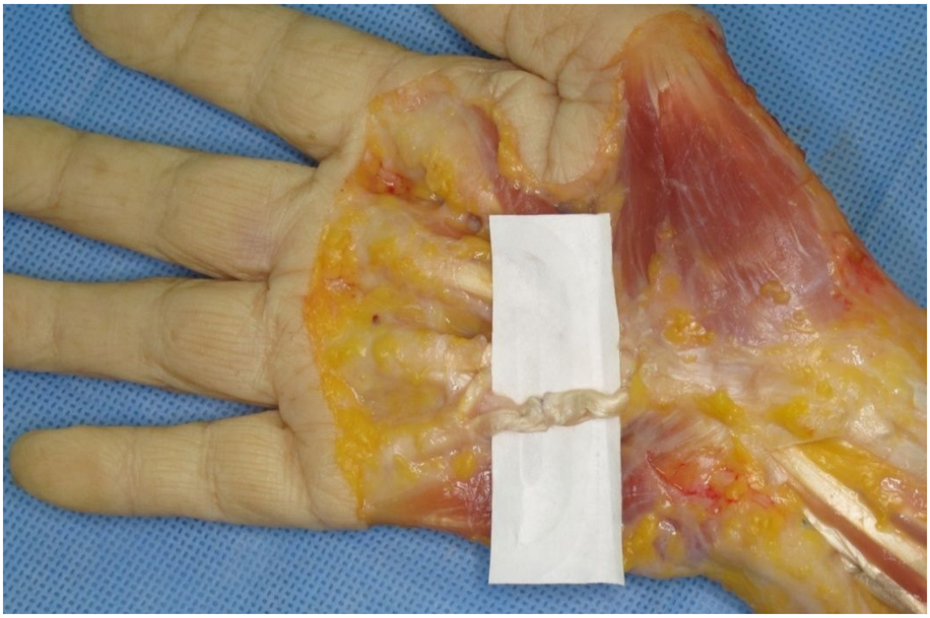


Figure 7. **Shortening of the 5th FDP tendon**

The fifth FDP tendon was incised 5 mm at a level of zone 3 and repaired end-to-end with a modified Kessler method.

RESULTS

The quadriga phenomenon that occurred the fourth finger is demonstrated in Figures 8, 9, and 10. When the fifth FDP tendon was shortened, the ROM of fourth finger was in deficit, by an amount related to the amount of fifth

FDP tendon shortening. The flexion angles of the DIP, PIP and MCP joints of the fourth finger were increased when the fifth FDP tendon was shortened 5mm, 10mm, and 15mm respectively.

The flexion angles of each joint of the fourth finger are summarized in Table 1. The average flexion angles of each joint after shortening of the fifth FDP tendon are shown in Table 2. There were significant differences in the flexion angles of the DIP, PIP and MCP joints of the fourth fingers among the shortening of the fifth FDP tendon ($p < 0.001$ for all joints). However, there were no significant differences in the flexion angles of the DIP, PIP, and MCP joints of fifth fingers ($p = 0.148$ for the DIP joint, $p = 0.184$ for PIP joint, $p = 0.198$ for the MCP joint).

Extension lag (180 degrees – flexion angle) was also considered in the statistical analysis. The extension lag of the DIP, PIP and MCP joint angle of fourth finger varied linearly with shortening of the fifth FDP tendon (Figs. 11, 12, 13). The extension lag of the fourth DIP joints was correlated with the amount of shortening of the fifth FDP tendon. The regression equation for the DIP joint was $Y = -2.17X + 60.0$ ($R^2 = 0.616$, $p < 0.001$), where Y is the amount of extension lag of the DIP joint and X is the amount of fifth FDP tendon shortening (mm). Similarly, regression equations for the PIP and MCP joints were $Y = -1.67X + 81.68$ ($R^2 = 0.392$, $p < 0.001$) and $Y = -1.25X + 79.65$ ($R^2 = 0.548$, $p < 0.001$) respectively.

The change in excursion of the fourth FDP tendon after shortening of the fifth FDP tendon is shown in Table 3. The regression equation for this relationship was Y = - 0.926X + 32.52 ($R^2 = 0.505$, $p < 0.001$), where Y is the change of excursion of the fourth FDP tendon and X is the amount of fifth FDP tendon shortening (mm).

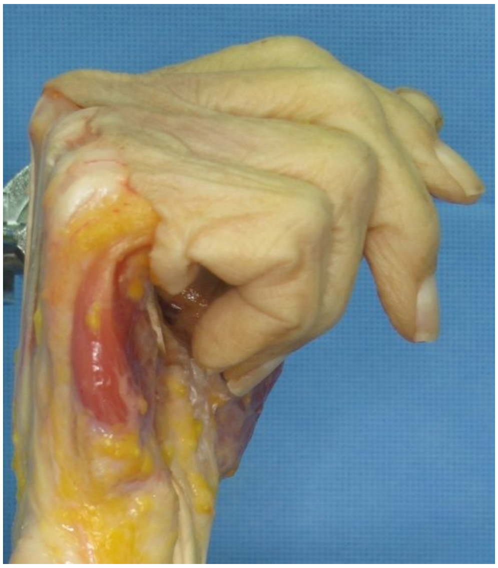


Figure 8. Result after 5 mm shortening

The quadriga phenomenon occurred after the fifth FDP tendon was shortened.

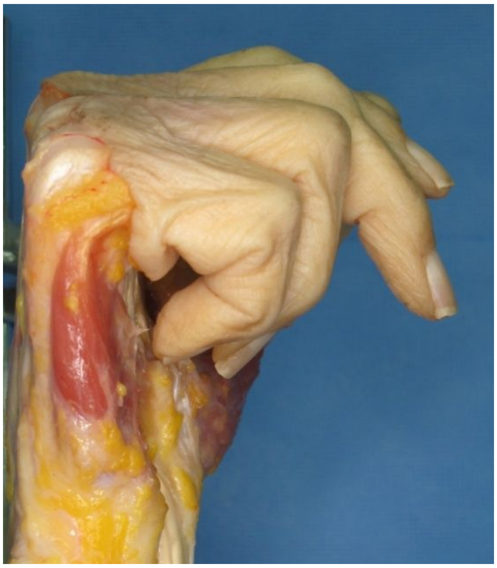


Figure 9. Result after 10 mm shortening

Figure 10. Result after 15 mm shortening

Table 1. The flexion angles of DIP, PIP and MCP joint of the 4th finger

Cadaver			DIP	PIP	MCP
1	4th	0mm	122	102	109
		5mm	132	112	118
		10mm	148	118	121
		15mm	154	127	125
	5th	0mm	109	92	100
		5mm	110	94	105
		10mm	112	96	104
		15mm	102	98	108
2	4th	0mm	113	100	103
		5mm	119	108	110
		10mm	142	118	119
		15mm	150	126	121
	5th	0mm	102	93	100
		5mm	104	94	100
		10mm	103	92	102
		15mm	104	94	103
3	4th	0mm	120	90	102
		5mm	152	111	104
		10mm	161	113	110
		15mm	150	123	114
	5th	0mm	112	99	92
		5mm	118	101	93
		10mm	120	106	102
		15mm	123	104	100
4	4th	0mm	130	87	92
		5mm	140	100	90
		10mm	157	109	100
		15mm	162	117	112
	5th	0mm	120	83	87
		5mm	117	89	90
		10mm	118	88	91
		15mm	120	90	95
5	4th	0mm	135	92	98
		5mm	142	99	104
		10mm	150	102	109
		15mm	158	125	113
	5th	0mm	110	89	90
		5mm	112	90	91
		10mm	113	92	91
		15mm	111	95	92

Cadaver			DIP	PIP	MCP
6	4th	0mm	124	100	103
		5mm	131	105	106
		10mm	143	115	114
		15mm	152	124	123
	5th	0mm	110	94	100
		5mm	108	98	104
		10mm	111	100	102
		15mm	112	100	107
7	4th	0mm	110	99	101
		5mm	118	110	109
		10mm	134	119	121
		15mm	148	130	124
	5th	0mm	102	93	102
		5mm	104	94	104
		10mm	103	92	105
		15mm	104	94	105
8	4th	0mm	113	93	110
		5mm	121	100	114
		10mm	135	115	123
		15mm	149	130	128
	5th	0mm	105	98	100
		5mm	111	100	103
		10mm	118	99	108
		15mm	123	102	110
9	4th	0mm	113	98	102
		5mm	121	102	107
		10mm	132	111	110
		15mm	140	120	112
	5th	0mm	110	94	92
		5mm	112	99	93
		10mm	113	100	94
		15mm	116	100	94
10	4th	0mm	120	96	100
		5mm	124	99	105
		10mm	132	105	110
		15mm	138	112	113
	5th	0mm	102	90	95
		5mm	104	91	96
		10mm	104	92	96
		15mm	105	94	97

Table 2. The mean flexion angles of each joint after shortening of the fifth FDP tendon

		0 mm	5 mm	10 mm	15 mm
4th finger	DIP	120.0 ± 8.1	130.0 ± 11.5	143.4 ± 10.4	150.1 ± 7.3
	PIP	96.7 ± 5.0	104.6 ± 5.3	112.5 ± 5.7	123.4 ± 5.7
	MCP	102.0 ± 5.1	106.7 ± 7.4	113.7 ± 7.2	118.5 ± 6.3
5th finger	DIP	108.2 ± 5.7	110 ± 5.1	111.5 ± 6.3	112.0 ± 8.2
	PIP	92.5 ± 4.6	95.0 ± 4.3	95.7 ± 5.5	97.1 ± 4.4
	MCP	95.8 ± 5.3	97.9 ± 5.9	99.5 ± 6.0	101.1 ± 6.4

Data represent the mean (degrees) ± SD

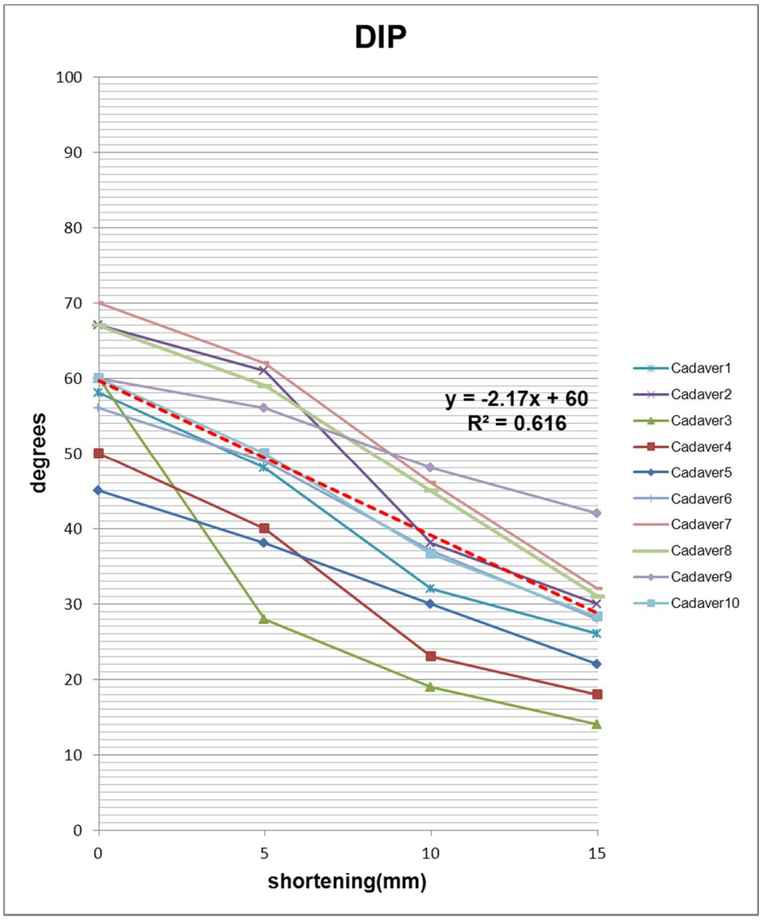


Figure 11. The extension lag of the fourth DIP joints vs the shortening of the fifth FDP tendon in each cadaveric forearm

These showed linear correlation with the degree of shortening (R^2 = 0.616, p < 0.001).

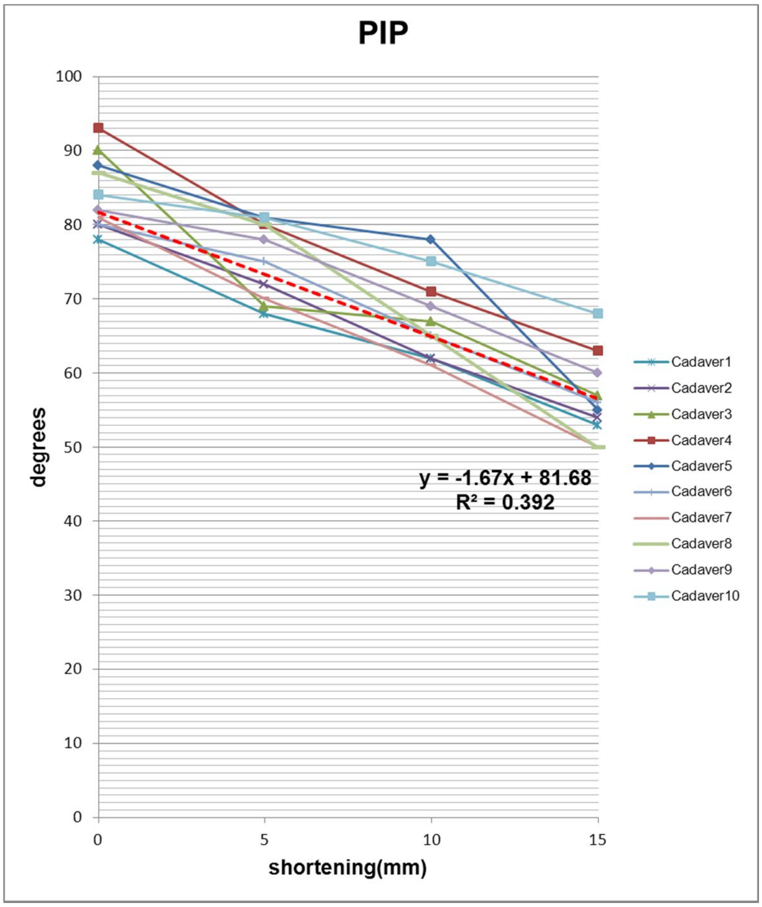


Figure 12. The extension lag of the fourth PIP joints vs the shortening of the fifth FDP tendon in each cadaveric forearm

These angles showed linear correlation with the degree of shortening (R^2 = 0.392, $p < 0.001$).

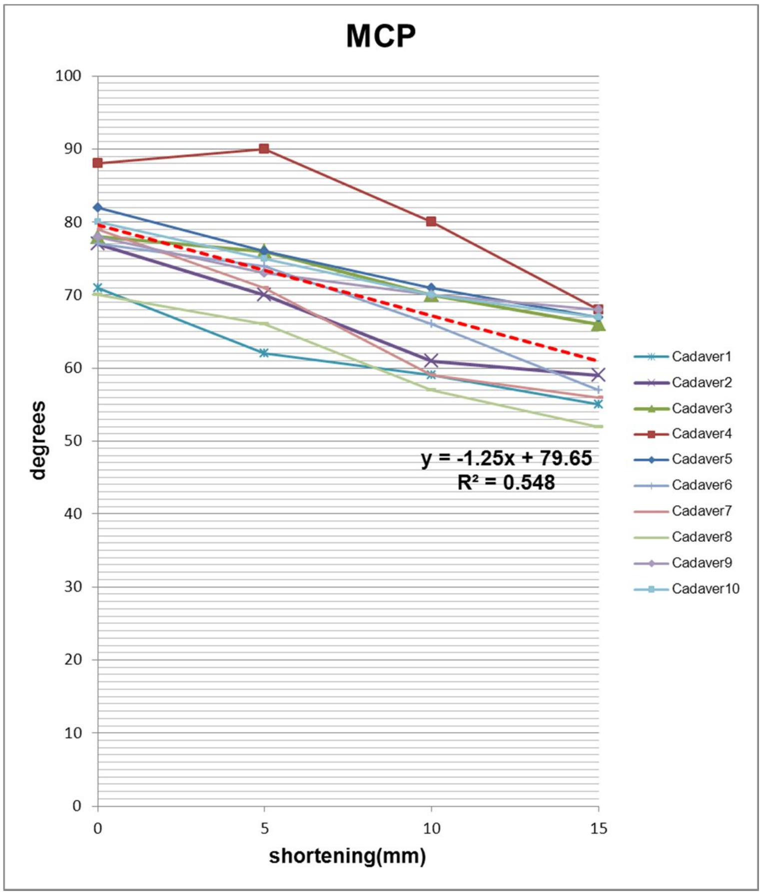


Figure 13. The extension lag of the fourth PIP joints vs the shortening of the fifth FDP tendon in each cadaveric forearm

These showed linear correlation with the degree of shortening ($R^2 = 0.548$, $p < 0.001$).

Table 3. The excursion of the fourth FDP tendon

Cadaver		4th FDP excursion
1	0mm	36.7
	5mm	33.6
	10mm	27.6
	15mm	23.4
2	0mm	32.4
	5mm	30.5
	10mm	25.7
	15mm	21.5
3	0mm	30.6
	5mm	26.6
	10mm	22.6
	15mm	20.4
4	0mm	29.5
	5mm	20.5
	10mm	12.2
	15mm	10.4
5	0mm	28.5
	5mm	24.8
	10mm	20.2
	15mm	18.5
6	0mm	38.6
	5mm	34.5
	10mm	29.4
	15mm	22.3
7	0mm	35.3
	5mm	29.8
	10mm	23.2
	15mm	19.2
8	0mm	32.7
	5mm	29.2
	10mm	24.1
	15mm	22.6
9	0mm	36.3
	5mm	30.5
	10mm	23.6
	15mm	20.2
10	0mm	26.2
	5mm	20.1
	10mm	16.5
	15mm	12.3

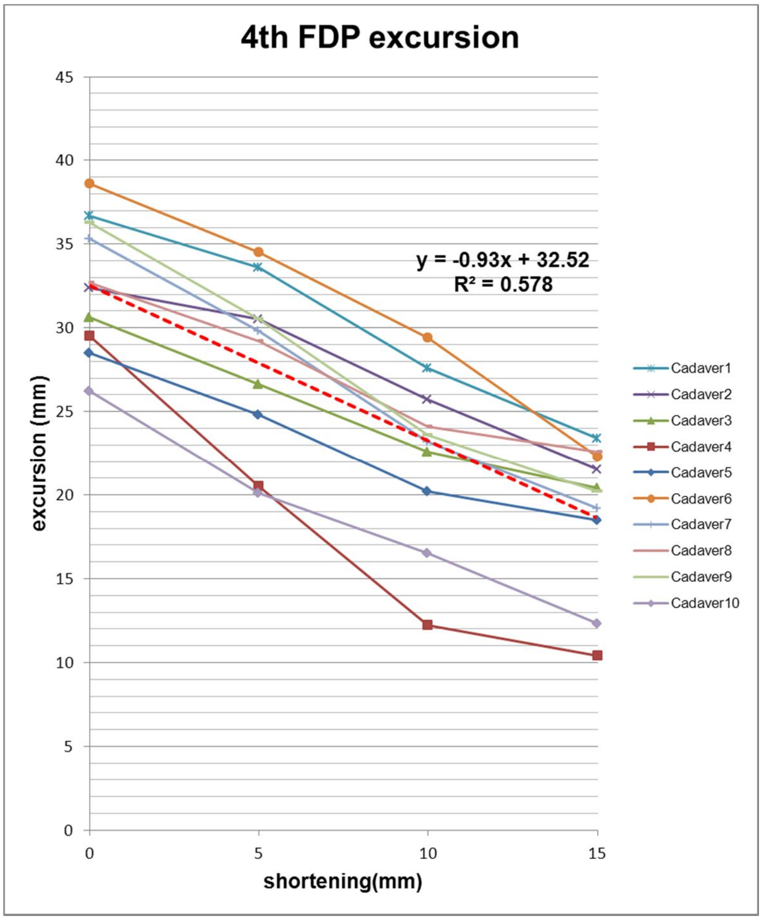


Figure 14. The excursion of the fourth FDP tendon

It was negative correlation with the degree of shortening of the fifth FDP tendon (R^2 = 0.578, $p < 0.001$).

DISCUSSION

The quadriga phenomenon was first described by Bunnel[1], who observed "As the flexor tendons arise from practically a common muscle belly, the function of one tendon limits the excursion of the rest of the tendon". The phenomenon was termed "Quadriga" by Verdan[15], who compared the common muscle belly of the FDP to Roman four horse chariot and the four tendons to the reins of four horses.

The effect of the quadriga phenomenon was been noted in a variety of clinical situations. It has been seen when full proximal excursion of one of the FDP tendons was prevented by holding one or more fingers in extension. The FDS tendon excursion and strength can be tested by keeping the adjacent fingers in extension[12]. Schweizer reported that rock climbers made use of the quadriga phenomenon in the slope grip position[13]. The strength and load increased up to 48% in one finger holds compared to all finger holds. It has also been noted that after finger joint arthrodesis or amputation, grip strength and adjacent finger flexion were limited because of this phenomenon[8,9].

We were able to demonstrate the quadriga phenomenon after FDP tendon shortening in a cadaver model. Further we were able to formulate this phenomenon using a simple linear equation. Our results showed that depending on the amount of the fifth FDP tendon shortening, flexion of the IP and MCP joints of the fourth finger was limited. Linear regression showed that the amount of shortening of the fifth FDP tendon was more influential over the flexion angle of the DIP joint than the flexion angles of other joints. According to our regression equation, shortening of the fifth FDP tendon by 1 mm would reduce the ROM of fourth finger by approximately 5 degrees. Also, the excursion of fourth FDP tendon was reduced by an amount dependent on the amount of shortening of the fifth FDP tendon. Although the excursion of the fourth FDP tendon differed for each cadaveric forearm, there was a consistent tendency to decline depending on the excursion of the fifth FDP tendon due to the quadriga phenomenon. Clinical implications were noted when we repaired fifth FDP tendon, prevention of the quadriga phenomenon was only noted when the tendon was repaired such that its original length was restored.

There were several limitations in our study. First, we did not consider the interconnectedness of the FDP tendon. In a recent study, some interconnections between FDP tendons were noted[12]. From proximal to distal, interconnections are existing within the muscle bellies, cross-linking of tendon fibers in the distal forearm and carpal tunnel, synovial sheaths interconnecting between tendons in the carpal tunnel and resulting from the tight origins of lumbricals originating from two adjacent tendons. We focused on the common muscle belly of the fourth and fifth FDP for simplification in the cadaveric model. The attempt to preserve other anatomical structures meant that we did not investigate the interconnections between the FDP tendons. These interconnections may have influcenced our results. Second, the number of cadaveric forearms was small, hence the non-parametric form of the analysis of variances (ANOVA) was used and we did not perform multiple comparison (post hoc) tests. Third, we measured the flexion angle with a goniometer. To improve accuracy in measuring angles, radiographic evaluation or motion analyses could be helpful. Fourth, the amount of shortening is in reality a continuous quantitative variable, but we considered just three sequential amounts of shortening for practical reason. This may have introduced a degree of error into the regression equation.

In conclusions, this study successfully demonstrated the quadriga phenomenon in a cadaveric model with fifth FDP tendon shortening. Our results indicate that after fifth FDP tendon injury, it is important to restore the tendon to its original length accurately to ensure adequate function of adjacent fingers.

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국문 초록

서론: 사두마차 현상은 손상된 심수지 굴곡건의 이동거리가 단축되어 인접한 정상 손가락의 굴곡이 감소하는 상황을 의미한다. 사두마차 현상은 많은 임상 상황에서 발생할 수 있으며, 수부의 기능을 감소시킨다. 본 연구의 목적은 신선 사체에서 정상과 심수지 굴곡건이 단축된 모델에서 생역학적 요인의 변화를 분석하고, 제 5 수지 심수지 굴곡건이 단축된 모델에서 사두마차 현상이 발생함을 증명하여, 손상된 건 복원 시 기능의 정상적인 회복을 위해서 정확한 길이로 봉합하는 것이 필요하다는 것을 제시하는 데 있다.

방법: 10 개의 신선동결 사체의 전완부를 대상으로 실험을 진행하였다. 심수지 굴곡건과 신전건을 박리하여 준비한 후 고정대에 고정한다. 제 5 수지가 완전 굴곡된 상태의 장력을 측정하고, 제 4 수지의 심수지 굴곡건의 이동거리, 제 4 수지 및 5 수지의 원위 및 근위지간관절과 중수지관절의 각도를 측정하였다. 제 5 수지의 심수지 굴곡건 단축 모델을 굴곡건 제 3 구역에서 제 5 수지 심수지 굴곡건을 5 mm 절단하여 단축한 후 봉합하여 만들었다. 이전에 측정했던 척도들을 다시 측정하였다. 같은 방법으로 10 mm, 15 mm 단축 모델을 만들어 척도들을 측정하였다.

결과: 제 5 수지 심수지 굴곡건의 단축 정도에 따라 제 4 수지의 굴곡범위는 줄어들었다. 즉 제 4 수지 원위 및 근위지간관절과 중

수지관절의 굴곡 각도는 제 5 수지 심수지 굴곡건을 5 mm, 10 mm, 15 mm 단축함에 따라 증가하였다. 신전제한 각도는 제 5 수지 심수지 굴곡건 단축 정도와 선형관계를 가지고 있었으며, 선형회귀모델로 다음과 같은 식을 추정할 수 있었다. 원위지간관절의 신전 제한 각도 Y = -2.17X + 60.0 (R^2 = 0.616, p < 0.001), 근위지간관절의 신전 제한 각도 Y = -1.67X + 81.68 (R^2 = 0.392, p < 0.001), 중수지관절의 신전 제한 각도 Y = -1.25X + 79.65 (R^2 = 0.548, p < 0.001). 또한 제 4 수지 심수지 굴곡건의 이동거리 Y = - 0.926X + 32.52 (R^2 = 0.505, p < 0.001) 로 추정되었다,

결론: 이번 연구에서 제 5 수지 심수지굴곡건 단축 모델을 통하여 사두마차 현상을 증명하였다. 결론적으로 제 5 수지 굴곡건 손상의 봉합 시 최선의 결과를 얻기 위해서는 건의 원래 길이로 복원하는 것이 필요하다.

주요어 : 사두마차 현상, 심수지 굴곡건, 신전제한, 건 이동거리, 사체 연구

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