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Original Research

Experimental Evaluation of the Elson Test Efficiency Following Central Slip Injury

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ABSTRACT

Purpose: The purpose of this article is to explore the amount of work, quantitated by flexion and extension cycles, that is needed to obtain a positive Elson test following a central slip injury.
Methods: Thirteen frozen cadaveric fingers from individuals with an average age of 79.6 years were used. Testing was performed by imposing sinusoidal displacement of the 2 tendons, with loads ranging from 30 N to 2 N at 1 Hz. Following transection to the central slip, each finger was cycled 1,000 times using the same protocol adopted for the control. Following 100, 200, 300, and 1,000 cycles, we measured the extension angles of the metacarpophalangeal, proximal interphalangeal, and distal interphalangeal joints from the flexed position and the distance between landmarks of the extensor apparatus and simulated an Elson test.
Results: In both the fingers, the range of motion of the metacarpophalangeal and distal interphalangeal joints measured in the controls remained unchanged, whereas the range of motion of the proximal interphalangeal joint was significantly reduced immediately after central slip transection. Combining both ring and middle fingers, for a displacement of 5 mm, the force measured in the control (1.05 ± 0.69 N) increased to the value of 2.36 ± 0.97 N at the 1,000th cycle. Although the middle finger has shown a significant difference in force at 100 cycles following central slip transection, 200 cycles were needed to observe a difference on the ring finger.
Conclusions: In controlled conditions, there is a variation in resistance to flexion of the distal interphalangeal joint. However, the amplitude of the forces is so small that they are likely imperceptible clinically. Delayed testing should be considered to increase the sensitivity of the test or in patients experiencing pain.
Type of study/level of evidence: Diagnostic V.

Extensor tendons of the forearms and hands account for approximately 17% of all tendinous and ligamentous injuries, with most of these occurring in the extensor zone III (12.6%) than in any other anatomic zone.[1,2] Zone III extensor tendon injuries are characterized by central slip (CS) disruption at the proximal interphalangeal (PIP) joint and can result in the classic Boutonniere deformities.[3] Nalebuff and Millender[4] described staging of these deformities, with stage 1 defined as synovitis of the PIP joint with fully correctable extensor lag. Stage 2 entails contracture of the transverse fibers of the retinacular ligaments holding the lateral bands in a volarly subluxated state. Progression to stage 3 occurs when the destruction of the PIP joint and hyperextension of the metacarpophalangeal (MCP) joint stiffen the deformity.[4]

In the acute setting, diagnosis of CS disruption can be difficult due to preserved active extension of the PIP joint through the lateral bands and the fact that these injuries frequently present without any characteristic radiographic abnormality.[5] Pain, typically most severe over the dorsal PIP joint, may also limit proper examination of the CS.[6,7]

Declaration of interests: No benefits in any form have been received or will be received by the authors related directly or indirectly to the subject of this article.

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Early recognition of CS damage has been shown to lead to better clinical outcomes.[8] A Boutonniere deformity can develop after 2–3 weeks without treatment, and outcomes with conservative treatment starting 8 weeks after injury are unpredictable.[9] Treatment of acute closed injury involves full extension orthosis fabrication for 6 weeks, whereas serial orthosis fabrication to achieve PIP joint extension is recommended for injuries that have reached stage 3 ("complex") of the Nalebuff classification.[10,11] If full passive PIP joint extension cannot be achieved by serial orthosis fabrication within 6–12 weeks or if there is a bony avulsion with displacement greater than 2 mm that occurs concomitant with injury to the CS, then operative intervention with extensor mechanism repair and pin placement for 6 weeks has been recommended.[12,13] Several surgical techniques are available, but 6 weeks of splinting is advised after surgical treatment as it is for conservative approaches.[14,15]

The Elson test, used for the diagnosis of the CS rupture, is performed by asking the patient to extend the PIP joint against resistance from a 90° flexed position over the edge of a table and assessing the resistance of DIP joint to flexion.[7] This test, being the only test of CS integrity to identify damage before the development of Boutonniere deformity, is more reliable than other physical examination tests. It is also more reliable in patients with passively correctible deformities.[16] Literature supports its use as the standard test to detect CS rupture, although Elson has made it clear in his description of the examination that it would not be able to detect a partial disruption of the CS.[7,17]

It has been previously suggested that repetitive flexion of the PIP joint following CS injury could attenuate the triangular ligament and oblique fibers of the interosseous insertion, resulting in palmar subluxation of the lateral band inducing a Boutonniere deformity.[16] Diagnosis of CS injury is hindered by the active extension that may have been retained immediately after injury and by the difficult interpretation of the amount of extension needed for the Elson test.[18,19] Since the timing at which CS disruption is diagnosed impacts the treatment options available to the practitioner, the primary aim of this article was to quantify the number of cycles of flexion and extension following CS injury needed to obtain a notable resistance of DIP joint to flexion, characteristic of a positive Elson test. To better understand the stages of deformity previously documented in the literature, we also aimed to evaluate the changes in the extensor hood structures following CS injury and their influence on the finger kinematics.[4] We hypothesized that there is an increased resistance of the DIP joint to flexion, characteristic of a positive Elson test, immediately after injury despite the absence of notable anatomic changes in the extensor hood.

Materials and Methods

Specimen preparation

Thirteen frozen cadaveric middle and ring fingers from individuals with an average age of 80 ± 7 years were used. Disarticulation at the wrist was performed in a flexor and extensor tendon sparing manner. A 6-cm incision over the dorsal PIP joint was used to expose the CS. A 3-0 Ethibond suture (Ethicon Inc) and a simple interrupted stitch were used to mark characteristic elements of the extensor apparatus (Fig. 1): medial (MDC) and lateral (LDC) margins of the distal central tendon, outer margins of the medial (OML) and lateral (OLL) bands, and medial (MTL) and lateral (LTL) proximal insertions of the triangular ligament on the lateral bands. We measured the distance from the OML to OLL in correspondence of the PIP joint as a measure of the distance between lateral bands and the distance from MTL to LTL to evaluate the proximal width of the triangular ligaments; the distance from OLL to LTL and from OML to MTL to evaluate the distal length of the lateral bands; and the distance from MDC to MTL and from LDC to LTL as measures of the proximal migration of the CS that is directly responsible for the extensor hood stretching, which has been indicated in the original manuscript of Nalebuff and Millender[4] to be leading cause for Boutonniere deformity.

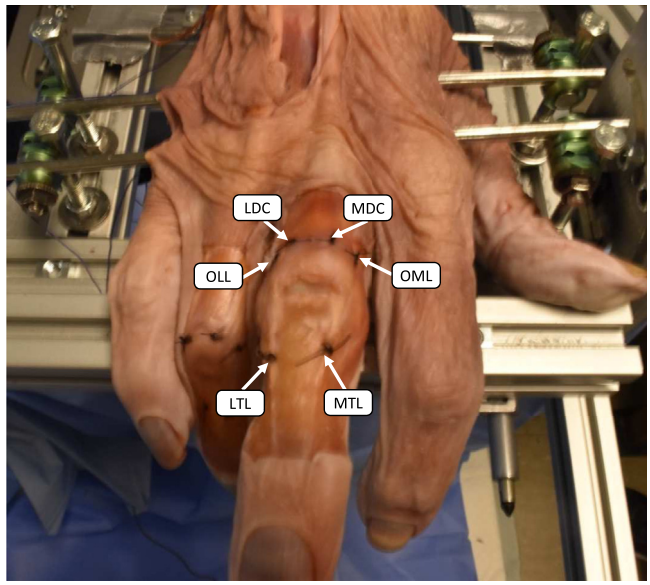

Figure 1. Landmarks of the extensor hood on the middle finger.

Mechanical testing

Pins placed transversely through the metacarpals were used to attach each hand to a custom apparatus mounted on a dynamic testing machine Instron E3000 (Instron). Using a size 0 Ethibond Excel suture (Ethicon Inc), the extensor and flexor digitorum tendons were tied with a running lock stitch to the 2 chains actuated by the Instron (Fig. 2A).

Testing was performed after preconditioning with 100 cycles by cycling the fingers between the motions of flexion and extension for 100, 200, 300, and 1,000 cycles and performing an instrumented Elson test at each interval. The cycling between flexion and extension was performed at a frequency of 1 Hz and obtained through the alternate displacement of the extensor and flexor tendons (Fig. 2B) through a system of pulleys, with loads ranging from 2 to 30 N. While the extensor tendon was loaded, the flexors were unloaded, and vice versa. The load of 30 N was chosen to approximate the loads found by Schuind et al[20] for the active unresisted flexion of the PIP joint, whereas the minimal load of 2 N was kept as tensioning load to avoid uncontrolled slack in the pulley system of the apparatus. During cyclic testing, the fingers were free to extend, but flexion was limited in the MCP and PIP joints by the apparatus that resembled the rigid edges of the table surface, typical of the Elson test.[7] An initial Elson test on the intact finger was performed after a preconditioning set of 100 cycles. Following the first Elson test, the CS was transected with a lateral band sparing transverse incision through the CS and joint capsule with a #15 Bard-Parker scalpel blade (Aspen Surgical). Each finger was then cycled 1,000 times using the same protocol adopted for the control. The measure of the joints' range of motion (ROM) and instrumented Elson tests were performed at 100, 200, and 300 cycles to evaluate the effects of the CS transection in the short term and at 1,000

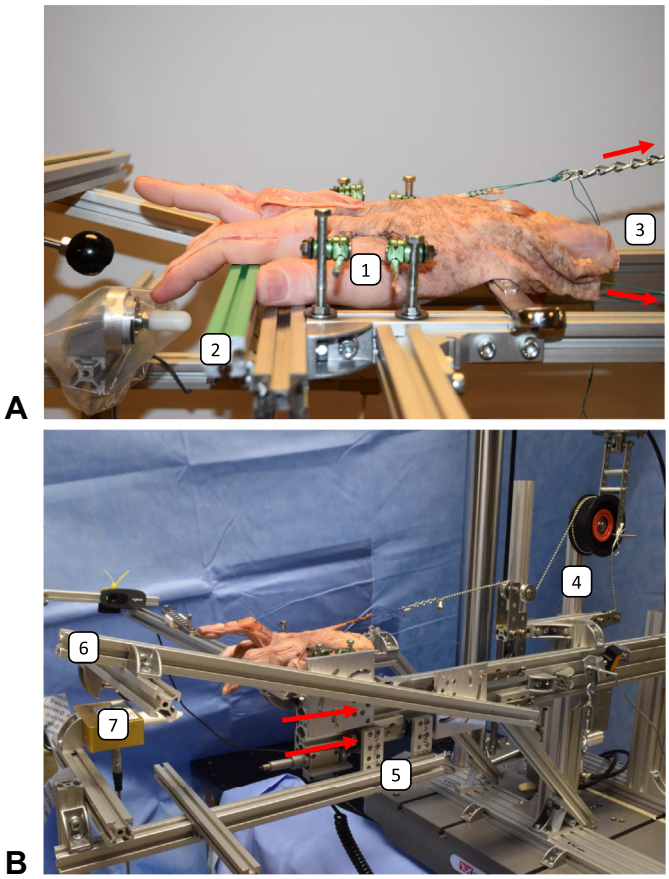

Figure 2. A Detailed and **B** panoramic views of the custom apparatus used for the mechanical testing showing the pins used to secure the hand (1), rigid edges of the table surface typical of the Elson test (2), the sutures used to tie extensor and flexor digitorius (3) to the chains actuated by the Instron (4), and the system or rails (5) used to advance the posts (6) and (7) positioned on the middle phalanx and the fingertip, respectively.

cycles for the long term. Measures at intermediate cycles were not taken to limit the time needed to execute the experiments. The MCP, PIP, and DIP joint angles were measured through digital images of the finger taken in full extension and flexion against the rigid surfaces resembling the table as used in the classic description of the Elson test. Joint angles were measured by importing the acquired images in Rhinoceros 6 (Robert McNeel & Associates), and for each joint, the ROM was computed by the senior investigator (G.S.) as the difference in joint angle achieved in full extension from the joint angle in the resultant flexion achieved against the surface resembling the table edge indicated by Elson.[7]

Instrumented Elson test

The instrumented Elson test, specifically developed for the study, was performed in 4 stages: (1) In the first stage, a 30 N force was applied to the flexors to obtain the PIP joint in flexion against the edge of the apparatus that functioned as a tabletop.[7] (2) While the flexor tendons were tensioned, a post was placed at the midpoint of the middle phalanx to simulate the physician's thumb resistance to extension (Fig. 3). (3) The load on the flexor tendons was removed, and a load of 30 N was applied to the extensor tendon and maintained. (4) In this flexed posture, while the extensor was kept loaded, the DIP joint resistance to flexion was estimated, measuring the force needed to displace the fingertip 2.5 mm and 5 mm toward DIP joint flexion. These displacements were arbitrarily chosen by the surgeon to best resemble the Elson test performed on real fingers and imposed advancing the post on the fingertip along a rail. Consistency in the post placement and fingertip displacement was guaranteed by 2 digital micrometers (LMI Corp), whereas the force was measured using a Futek LRF400 (Futek Inc) load cell.

Statistical analysis

The Shapiro-Wilk test was used to determine the normality of the data. To determine the effects and progression of CS transection, measures taken after CS transection were compared with those taken before transection and adopted as control. We performed repeated-measures analysis of variance or its nonparametric equivalent, robust analysis of variance, to determine significance where the finger under test constituted the group and the cycle count constituted the block criterion.[21] We normalized each of the measures to be expressed as a proportion of their control for this analysis. This was performed to account for the variance that may have occurred in individual measurements. Specific differences between cycles and equivalence between the left and right fingers were evaluated for the ROMs and the forces using paired t test or Wilcoxon signed rank sum for nonparametric data. We categorized the results as significant for $\alpha = 0.05$. We calculated Pearson correlation coefficient between all pairs of numeric variables. Two variables were considered to be correlated if the absolute value of their correlation coefficient was at least 0.5. Post hoc power analysis was performed on all the variables calculating Cohen's d and deriving the approximate sample size at which a power of 0.8 could be achieved for $\alpha = 0.05$. Results obtained for each finger, hand, and sample combination in the controls and the cycles with the greatest deviation from them were chosen to calculate the Cohen's d.

Results

ROM of the joints

We performed experiments on 13 fingers and found that the left (n = 6) and right (n = 7) fingers, prior to CS transection, showed the same ROM for all 3 joints ($P > .05$). In both fingers, the ROMs of MCP and DIP joints in the controls (37° ± 13° and 7° ± 14°, respectively) remained unchanged after CS transection and through the following 1,000 cycles ($P > .05$, Table 1). Combining both fingers, the PIP joint ROM of the control (59° ± 17°) was found to be significantly reduced to 41° ± 23° ($P < .05$) immediately after the CS transection occurred. The ring finger that in the control had a ROM of 66° ± 15° exhibited larger angles than the middle finger ($P < .05$) that was limited to 52° ± 16° for the control. Following the CS transection, the PIP joint ROM was reduced at the 1,000th cycle to 19° ± 25° for the ring and middle fingers combined, but such variation over the increasing cycles was not significant ($P > .05$, Fig. 4). Post hoc power analysis revealed that the PIP joint ROM was characterized by a large effect size ($d = 2.31$) that only required a minimum of 3 samples, whereas ROMs of the MCP and DIP joints resulted in a medium effect size that required 56 and 52 samples, respectively.

Forces measured through the instrumented Elson test

For both imposed displacements of 2.5 and 5 mm, the right and left fingers did not show a significant difference ($P > .05$). Combining both the ring and middle fingers, for a displacement of 5 mm, the force measured in the control increased from 1.05 ± 0.69 N

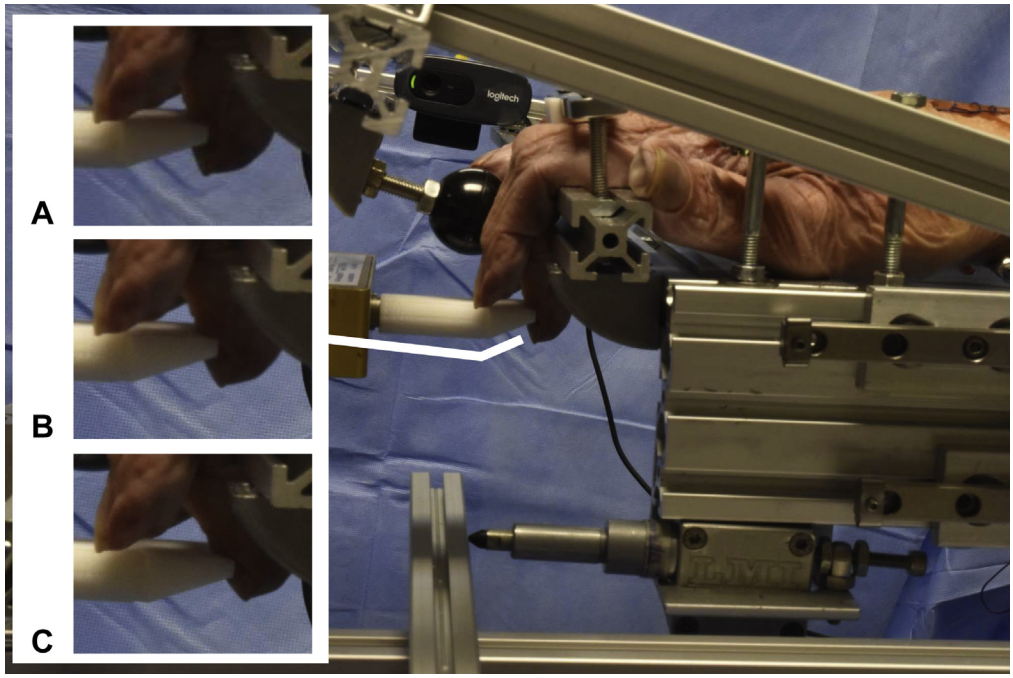

Figure 3. Sequential displacements at the DIP joint to impose flexion during the instrumented Elson test **A** at the beginning of the displacement, **B** at 2.5 mm, and **C** at 5 mm.

Table 1
Range of Motion Values Found for Both Middle and Ring Fingers Along With the Cycle of the First Significant Difference*

Joint	ROM in the Control, (SD)	ROM Following Damage, (SD)	ROM Measured at the 1,000th Cycle, (SD)	*P* Value for Finger Only	*P* Value for Cycles Only	*P* Value for Both Finger and Cycles	Cycle Showing Significant Difference Following Damage
MCP joint	37 (13)	37 (10)	41(16)	.01†	.59	.41	-
PIP joint	59 (17)	41 (23)	19 (25)	.01†	.01§	.11	0 ($P = .03$)
DIP joint	7 (14)	2 (15)	1 (15)	.01‡	.24	.11	-

* We express the results using 3 *P* values: the *P* value associated with the finger only (*P*[finger]), the *P* value associated with the cycle only (*P* [cycles]), and the *P* value for a given finger/cycle combination (*P* [finger × cycles]). The final column depicts the cycle at which a significant difference in ROM occured and its associated *P* value; only the PIP joint was applicable, which showed a significant difference from predamage conditions at cycle 0.
† $P < .01$
‡ Statistically significant.
§ $P < .001$

to 2.36 ± 0.97 N at the 1,000th cycle. The force increment was significant already at 100 cycles after the CS transection ($P = .03$) (Table 2). The observed increment of force with cycling was mainly determined by the middle finger ($P < .05$) since the ring finger did not show significant differences ($P = .08$). On direct comparison between the control and the measures taken following CS transection, for the 5 mm displacement, the middle finger showed a statistically significant difference at 100 cycles ($P < .05$), whereas 200 cycles were needed to observe a difference on the ring finger ($P = .05$). The large effect size found for the forces at both levels of displacements ($d > 2.24$) revealed that the number of samples was larger than the minimum needed ($n = 4$).

Changes in the extensor hood

The lateral bands at a distance (OML to OLL) of 12.2 ± 1.6 mm in the control exhibited significant widening ($P < .05$) that corresponded to the distance of 13.8 ± 1.5 mm immediately after CS transection (Fig. 5). The triangular ligaments (MTL to LTL), initially at a distance of 5.9 ± 1.4 mm in the control did not show significant widening for any cycle ($P > .05$, Table 3). The extensor hood overall dimensions (LDC to LTL and MDC to MTL) expanded during the cycling ($P < .05$), but such expansion was not determined by the distal elongation of the lateral bands (OLL to LTL and OML to MTL) ($P > .05$). The overall dimensions of the extensor hood, measured by the distances from LDC to LTL and from MDC to MTL, have shown the highest correlations with the ROMs measured for the PIP and MCP joints ($R^2 > 0.5$, Table 4). The distance between the lateral bands was moderately correlated to ($R^2 = 0.52$) the force needed to displace the fingertip by 2.5 mm and the ROM measured for the PIP joint ($R^2 = -0.59$). A large effect size ($d > 2.80$) was found for all the measures, with the exception of the distal length of the lateral bands (OLL to LTL and OML to MTL) that would have required more than 100 specimens to achieve the 80% power.

Discussion

Early detection and treatment of CS injury is necessary to prevent the development of a chronic or complex Boutonniere deformity.[22] Because the Elson test remains the standard test for CS disruption, it is crucial to evaluate its usefulness in the early stages.[17]

Immediately following CS transection, we found that the resistance to flexion of the DIP joint, characteristic of a positive Elson test, is statistically significant but may be imperceptible clinically.[7] We documented a difference in DIP joint resistance to flexion

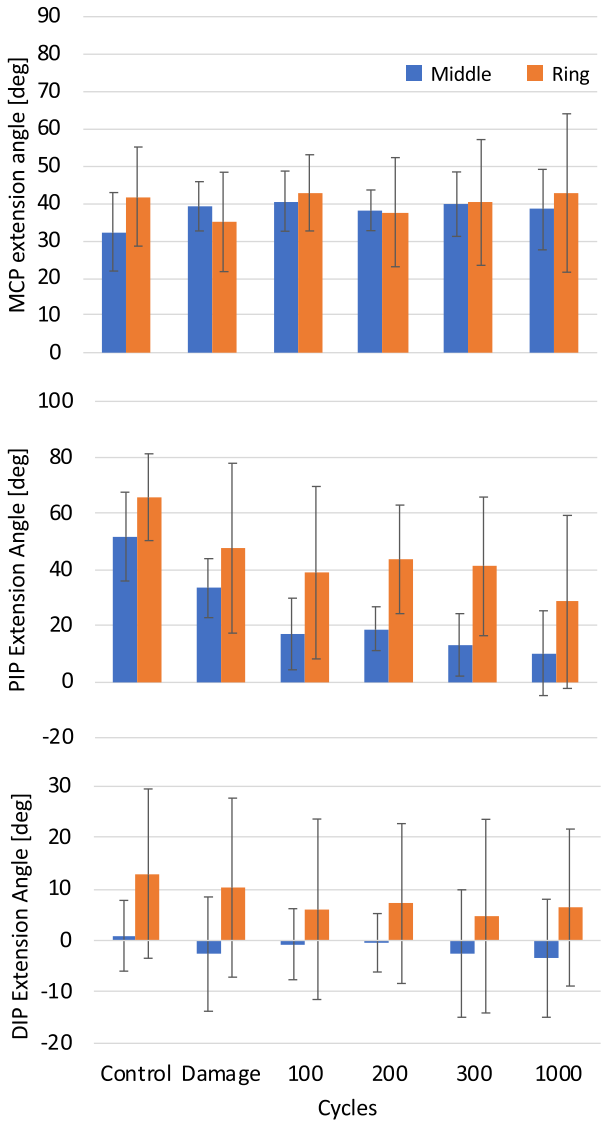

Figure 4. Changes in the joint extension angles for the middle and ring fingers from the control to 1,000 cycles.

between the middle and ring fingers, the cause and significance of which is unclear and needs further investigation.

The difference between the fingers in the effect of the cycles needed to see a change in resistance to DIP joint flexion raises a concern of false negatives if the finger being examined has not been used enough to produce a positive test, particularly if we consider that the middle finger is moved more frequently during daily activities than the ring finger.[23] The examiner must be aware of this discrepancy and the small amplitude of the forces involved. The largest average force has been found to be limited to 2.46 ± 1.17 N for the ring finger at the largest displacement of 5 mm. Although resistance to DIP joint flexion while performing the Elson test has never been measured, the tactile force perception by comparing forces varying by 20% increments from a 2.25 N base force has been studied (Allin et al, proceeding from the 10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2002). A 10% increase was required to detect a noticeable difference. This was similar to a study of perception of forces applied in different directions, which found that a variation of 13% is detectable for loads of 1.12–3.87 N (Dorjgotov et al, proceeding from the International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2008). The same study also reported that equal forces applied in different directions tend to be perceived as different forces; thus, although variations in the present study are larger than what are detectable, while comparing joint stiffness between injured and adjacent, the orientation of the patient's finger to the examiner should be identical to ensure repeatability of the test. Testing the DIP joint resistance to flexion by imposing an arbitrarily chosen fingertip displacement may be seen as a limitation, but it was enough to identify variations in the forces caused by the CS transection. The displacement of 5 mm was chosen by the surgeon as a value that was believed would give feedback similar to the Elson test performed under clinical conditions. The 2.5-mm displacement was chosen as intermediated value that contextualized our findings to cases in which pain impeded the mobility of the finger.[7] Larger displacements would have amplified the trend we have found, but the identification of a threshold value for the displacement needed to perform an Elson test requires further clinical investigation.

The 30-N load chosen for the cycling of the finger and for the instrumented Elson test can be seen as a limitation because it is smaller than the peak forces of the extensor muscles, but it is comparable to the tendon load of 34.3 N measured for active unresisted finger flexion.[20]

Although Nalebuff and Millender[4] described stages of deformities secondary to CS transection, the association of these stages to anatomical changes in the extensor apparatus has not been previously proven.[24] In the present study, we found that the proximal retraction of the CS ($P < .05$) as previously proposed was highly correlated to the variation in ROM observed for the PIP ($R^2 = -0.5$) and MCP ($R^2 = 0.57$) joints, whereas it was moderately correlated to the force needed for the Elson test ($R^2 = 0.43$).[4] Widening of the lateral bands has also been found to be correlated to the force used in the Elson test ($R^2 = 0.52$), and it is consistent with volar subluxation of the lateral bands, which constitutes Nalebuff's first stage.[4] Contrary to the previous hypotheses, in our study, the CS transection did not result in a widening of the triangular ligament.[4,24]

Loss of PIP joint extension along with retinacular ligament contracture comprises Nalebuff's second stage.[4] The decreased PIP joint extension is secondary to a shift in extension force from the transected CS (which is no longer load bearing as evidenced by the increased distance from LDC to LTL and from MDC to MTL) to the volarly subluxated lateral bands.[25] In our experiment, we found that an average PIP joint extension of 59° ± 17° in the control decreased to 40° ± 23° immediately after CS transection.

Change in the angular displacement is an indication that the central tendon is discontinuous, but it may have limited clinical relevance since there can be many reasons why someone is unable or unwilling to extend the joint fully. We found increased resistance to DIP joint flexion immediately after CS transection, corresponding to an extension lag that increased with continued cycling.

This reduction is greater than the 2.4° ± 1.3° decrease seen in Grau et al's[24] study following CS excision. In contrast to Grau et al,[24] the forces required to flex the DIP joint were measured in the present study, which could have led to this observation. Also, a different posture of the hand was used as a reference configuration in the 2 studies, and we applied a 30-N force to the flexor and extensor tendons in contrast to the 20-N force used by Grau et al.[24] After 1,000 cycles, we saw a reduction in the PIP joint ROM from the control value of 59° ± 17° to 19° ± 25°, which is larger than the 29.2° ± 9.6° decrease reported by Grau et al[24] when they excised the interosseous fibers and triangular ligaments in addition to the CS, which may explain the differences in observed values.[24] Despite observing a larger reduction in the PIP joint ROM within the

Table 2
Force Values Measured at the Fingertip for the Ring and Middle Fingers and the Combination of Both Fingers for the 2 Imposed Displacements*

Finger	Displacement, mm	Force in the Control, N (SD)	Force at 100 Cycles Following the Damage, N (SD)	Force at the 1,000th Cycle [N] (SD)	*P* Value for Finger Only	*P* Value for Cycles Only	*P* Value for Both Finger and Cycles	Cycle Showing Significant Difference	Force at Cycle of Significant Difference, N (SD)
Combined	2.5	0.61 (0.47)	1.25 (0.63)	1.51 (0.58)	.08	.01†	.36	-	-
	5	1.05 (0.69)	1.75 (0.60)	2.36 (0.97)	.01†	.01‡	.10	-	-
Ring	2.5	0.78 (0.57)	1.36 (0.77)	1.17 (0.66)	-	.08	-	100 ($P = .05$)	1.36 (0.77)
	5	1.38 (0.69)	1.78 (0.65)	2.46 (1.17)	-	.22	-	200 ($P = .05$)	1.91 (0.79)
Middle	2.5	0.42 (0.21)	1.30 (0.48)	1.31 (0.46)	-	.01§	-	100 ($P = .01$)	1.13 (0.47)
	5	0.66 (0.50)	1.71 (0.61)	2.41 (0.78)	-	.01§	-	100 ($P = .01$)	1.13 (0.47)

* As with Table 1, we express the results using 3 *P* values: the *P* value associated with the finger only (*P*[finger]), the *P* value associated with the cycle only (*P* [cycles]), and the *P* value for a given finger/cycle combination (*P* [finger × cycles]). In addition to providing a column showing where the significant difference occurs (if applicable), we also provide the force measured at that point with its SD.
† $P < .001$
‡ $P < .01$
§ Statistically significant.

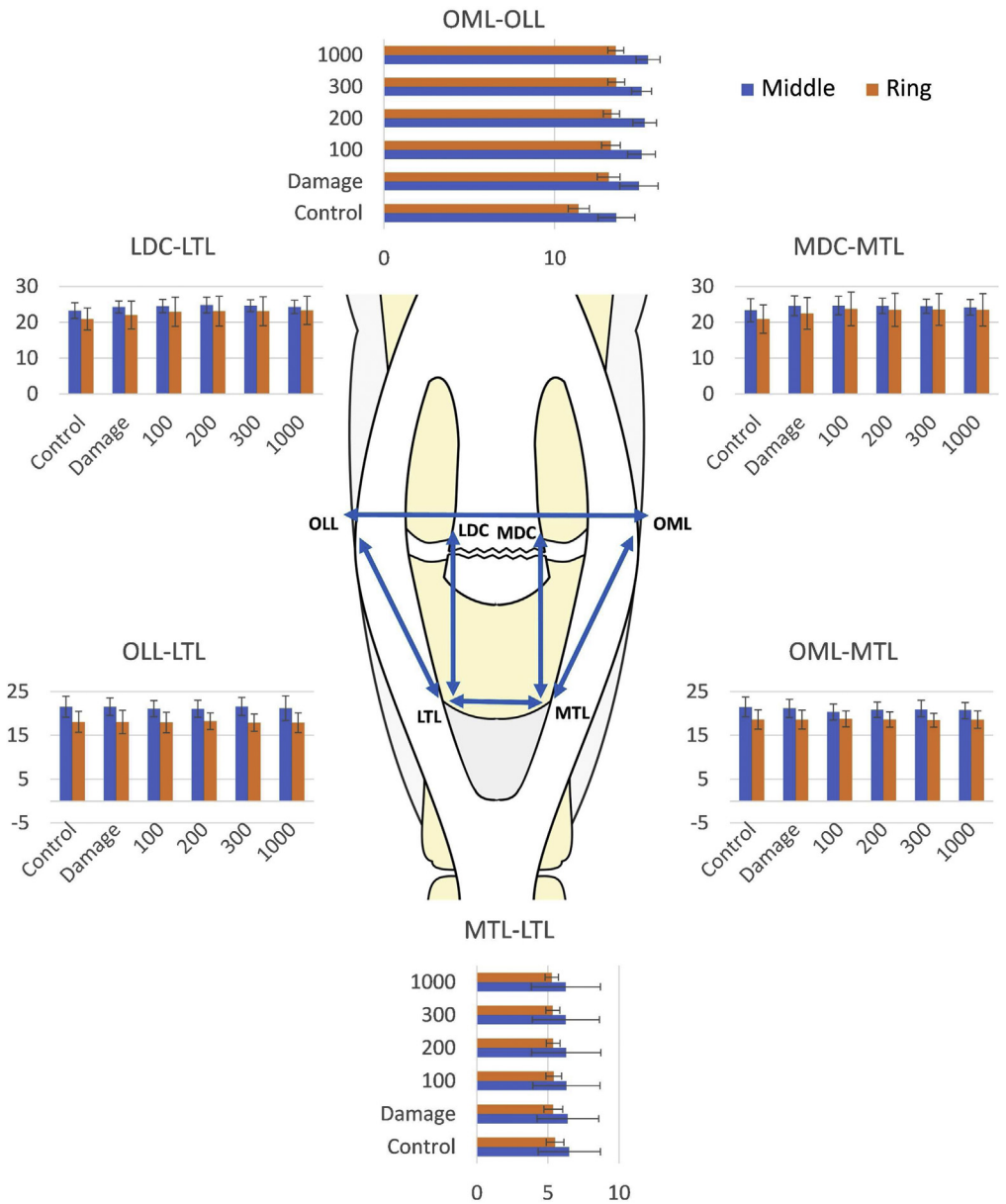

Figure 5. Distances expressed in mm between the anatomical landmarks of the extensor apparatus of the ring and middle fingers measured during the experiments: MDC and LDC are the medial and lateral margins of the distal central band; OML and OLL are the medial and lateral margins of the lateral bands; and MTL and LTL are the medial and lateral proximal insertions of the triangular ligaments on the lateral bands.

Table 3
Distances Measured on the Landmarks of the Extensor Hood for Both Fingers Combined*

Measured Distance	Measured Landmarks	Distance in the Control, mm (SD)	Distance Following Damage, mm (SD)	Distance Measured at the 1,000th Cycle, mm (SD)	*P* Value for Finger Only	*P* value for Cycles Only	*P* Value for Both Finger and Cycles§
Distance between lateral bands	OML to OLL	12.2 (1.6)	13.8 (1.5)	14.2 (1.3)	.03†	.01‡	.77
Triangular ligaments width	MTL to LTL	5.9 (1.4)	5.7 (1.4)	5.6 (1.5)	.17	.80	.89
Distal length of the lateral bands	OLL to LTL	19.8 (3.0)	19.7 (2.9)	19.5 (2.9)	.58	.38	.90
	OML to MTL	19.9 (2.6)	19.9 (2.4)	19.9 (2.4)	.01‡	.60	.11
Retraction of the central slip	LDC to LTL	21.9 (2.8)	22.9 (3.1)	23.6 (3.1)	.02†	.01‡	.38
	MDC to MTL	22.0 (3.6)	23.4 (3.6)	23.8 (3.4)	.01‡	.01‡	.19

* As with Table 1, we express the results using 3 *P* values: the *P* value associated with the finger only (*P*[finger]), the *P* value associated with the cycle only (*P* [cycles]), and the *P* value for a given finger/cycle combination (*P* [finger × cycles]).
† Statistically significant.
‡ $P < .001$
§ No measure was statistically significant for both the finger and cycles in combination, but with the exception of OML to MTL, any landmark that was significant for the given finger was also significant for the cycles.

Table 4
Correlation Coefficients Found Between the Distances of the Extensor Hood Landmarks and Resultant ROMs and Forces Needed During the Simulated Elson Tests

Measured Distance		MCP Joint	PIP Joint	DIP Joint	Force at 2.5 mm	Force at 5 mm
Central slip proximal retraction	MDC to OML	0	−0.25	0.01	0.23	−0.07
	LDC to OLL	0.45	−0.061	0.22	0.56	0.27
Distance between lateral bands	OML to OLL	0.35	−0.59	0.08	0.52	0.17
Triangular ligaments width	MTL to LTL	0.07	0.08	0.22	−0.2	−0.5
Distal length of the lateral bands	OLL to LTL	0.02	0.2	−0.13	0.23	−0.19
	OML to MTL	−0.41	0.52	−0.4	−0.08	−0.38
Proximal retraction of the central slip	LDC to LTL	0.55	−0.7	0.22	0.43	0.02
	MDC to MTL	0.57	−0.5	0.1	0.3	−0.3

considered number of cycles, our cadaveric model remained in a stage of pre-Boutonniere deformity that was interestingly characterized by the absence of triangular ligament widening.[16] In drawing these conclusions, we focused on the PIP joint because it has the largest active functional ROM.[26]

In the third stage proposed by Nalebuff, MCP joint hyperextension is expected; however, we did not observe significant extension of the MCP joint from the flexed position due to the limitation of its flexion by the apparatus, which was necessary to perform the instrumented Elson test properly. The placement of sutures to indicate anatomical landmarks of the extensor apparatus and measurement using a caliper may also present a limitation. However, a similar method has been used to mark and measure the pulley system of the thumb.[27] In addition, the skin incision was left open to facilitate the measurements of the anatomical landmarks of the extensor apparatus and to prevent the possibility of overtightening of sutures in closing, which was also performed in a study of the proximal A2 and A4 pulleys.[28] Electing not to close the skin incision could have resulted in desiccation of the tissues, but irrigation with saline solution was performed intermittently to maintain tissue hydration.[24]

Biomechanical investigations previously published on the extensor tendons have been used a number of specimens ranging from 5 to 20.[13,16,24,29,30] Cohen's effect size calculations revealed that the sample size used for this study was more than was needed for almost all the parameters. A greater sample size would have been needed for the proper identification of ROMs of the MCP and DIP joints and for the distal elongation of the lateral bands, but these elements were secondary to the aim of the study. Similar to the study by Grau et al,[24] we elected not to incorporate intrinsic musculature because of the complexity and potential interference of the musculature with repeatability of the testing.[24] The lumbricals primarily aid in a precision pinch and function in the extension of PIP and DIP joints while the MCP joint is flexed.[31] However, because the posture of a flexed MCP joint with extended PIP and DIP joints was not achieved at any point in the ROM of our cycling of the finger, it is unlikely that incorporating the lumbricals would have affected our findings. In addition, because of the insertion of the dorsal interosseous muscles on the extensor apparatus, similar results would be seen in fewer cycles for the development of DIP joint resistance to flexion and decreased PIP joint extension even if the dorsal interossei were included in the cadaveric model.[32] Further, it is important to note that most CS injuries are not the result of laceration or open injury as we tested but are closed.[13] The open wound modeled in this study was necessary to evaluate the progression of the deformity and the ability of the Elson test to detect this injury as it may occur in a complete closed disruption. However, if this degree of disruption were to occur in an open type injury, it would likely be surgically repaired, as open injuries that damage more than 50% of the CS necessitate open repair.[13] This study provides direct measures of the degree of deformation seen in the extensor mechanism as previously described by Nalebuff and Millender[4] and widely accepted in the literature. In conclusion, according to our findings, the resistance to flexion of the DIP joint should be immediately detectable after an injury in controlled conditions. However, the amplitude of the forces measured during the Elson test performed immediately following CS transection is so small that they are likely imperceptible clinically. An increase in the resistance and reduction of PIP joint ROM has been observed with cycling; thus, delayed testing should be considered to increase the sensitivity of the test or in patients experiencing pain. Our results indicate that 100–200 cycles are likely required to create the conditions necessary to detect a positive Elson test clinically.

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