Biomechanical Analysis of Flexor Digitorum Profundus and Superficialis in Grip-Strength Generation

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Abstract

Grip strength is generated through extrinsic flexor tendon and intrinsic muscle actuation. In the study reported here, we analyzed the grip-generating properties of the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) tendons during grip-strength generation.

In vivo gripping was reproduced in 11 cadaveric forearms through pneumatic tensioning of flexor tendons. A Jamar dynamometer (TEC, Clifton, NJ) was positioned in the hand at varying degrees of angulation measured between the Jamar compression axis and the second metacarpal.

Maximum gripping strength during isolated FDP and FDS tensioning generated maximum compressive forces at different angles ($P<.0001$). The isolated FDP showed continued increased grip strength with larger angles and was most effective when the dynamometer handle was in contact with the distal phalanx. The isolated FDS was most effective at smaller angles when the handle made contact with the middle phalanx. The isolated FDS shows an initial increase in grip strength as the contact point moves toward the middle phalanx ($P<.01$) and then a tendency for grip strength to decline as the contact point moves over the distal phalanx ($P<.01$).

The FDP and FDS tendons demonstrate unique abilities to generate compression on a dynamometer. This knowledge is important to consider when evaluating grip strength in patients who have injured the extrinsic finger flexors.

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Power grip is an isometric and static condition defined as forcible activity of the fingers and thumb acting against the palm to transmit force to an object. The fingers apply a force to counter the external forces of the object held.[1-3] The thumb is abducted and provides a reinforcing or buttressing action during extreme power grip.[1]

The flexor digitorum profundus (FDP) inserts onto the base of the distal phalanges of the index through small digits and flexes the wrist, metacarpophalangeal (MCP), proximal interphalangeal, and distal interphalangeal (DIP) joints. The FDP, a primary finger flexor, overpowers the interphalangeal extension force of the interossei during power gripping.[2] The FDP is not a primary flexor of the MCP joint and must overcome a poor mechanical advantage using the first annular pulley as a focus of its flexing capabilities.[4] The flexor digitorum superficialis (FDS) inserts onto the middle phalanges of the index through small digits and participates in power grip in direct proportion to the force required. The FDS is generally considered a reserve muscle that is summoned when increased force is required for finger flexion.[5] The extrinsic hand muscles provide the major force of gripping, as all the extrinsic flexor muscles exhibit a graded increase in the electromyographic activity during power gripping.[3,5]

The effect of forearm, wrist, and hand positioning on grip strength has been studied. The optimum position for maximum grip strength has been determined to be 35° of wrist extension, 7° of ulnar deviation, and neutral rotation.[6,7] Volar flexion, radial or additional ulnar deviation, and supination of 70° or more decrease grip strength.[6,8,9] The standard, adjustable-handle Jamar dynamometer (TEC, Clifton, NJ) has been widely used to measure grip strength and is reliable and accurate.[10-17]

Understanding the unique grip-generating properties of the FDP and FDS tendons is of critical importance in determining the extent of functional loss in patients with traumatic injury or destructive disease to the flexor tendons. It is also valuable for outcomes assessment after various surgical and rehabilitation procedures. Unfortunately, the grip-generating properties of the flexor tendons remain poorly understood. In the study reported here, we sought to identify characteristic behavior patterns of the FDP and FDS tendons during gripping motion. We asked these 6 questions:

1. When the FDP and FDS tendons are tensioned in isolation, are maximum compressive forces generated at different degrees of dynamometer angulation?
2. When the FDP tendons are tensioned in isolation,

what is the relationship between degree of dynamometer angulation and compressive force generated by the cadaveric hand on the Jamar handle?

3. When the FDS tendons are tensioned in isolation, what is the relationship between degree of dynamometer angulation and compressive force generated by the cadaveric hand on the Jamar handle?
4. Does the combined tensioning grip strength versus angulation curve behave as a combination of those curves generated during isolated FDP and FDS tensioning?
5. Does equal tensioning of the isolated FDS tendons compared with the isolated FDP tendons generate a significant change in maximal gripping strength?
6. What is the relationship between the Jamar compression measured during combined FDP and FDS actuation and the calculated additive maximum dynamometer compression forces generated during isolated and equal FDP and FDS tensioning?

Materials and Methods

The experimental setup consisted of a test table on which an arm-fastening device and pneumatic cylinders were mounted (Figures 1, 2). Eleven freshly frozen cadaveric upper extremities were chosen without gross deformities, arthritic changes, or prior surgeries. Each hand was thawed and dissected in a uniform manner. The distal humerus was severed at the midshaft level and the flexor compartment of the forearm carefully exposed. The individual FDP and FDS tendons were sutured to each other at the level of the flexor retinaculum before being secured with custom-designed steel clamps. This was done to preserve the native anatomy of the FDP and FDS tendons and preserve the digital cascade during gripping. The proximal muscle bellies were then resected. A thin, smooth pin was inserted through the second metacarpal head along its long axis. This longitudinal pin was used for measuring the angle between the second metacarpal and the compression axis of the dynamometer. Threaded pins were drilled into the diaphyses of the first, second, and third metacarpal bones. These pins were then fastened to an external fixator to maintain thumb abduction. The hand was maintained at 35° of wrist extension and 7° of ulnar deviation with steel wires secured to the experimental setup. This fixation prevented wrist flexion during tendon tensioning.[6] Flexor tendon clamps were then fastened to steel cables and tensioned with pneumatic cylinders through a cable-and-pulley arrangement.

The FDP and FDS were tensioned according to a loading algorithm that was consistent for all 11 arms. Potential grip reactive intertendon interaction was minimized through relief of tendon tension and full extension of the digits between grip-strength measurements. This maneuver was particularly important during simultaneous flexor actuation to minimize locking by the FDP on the FDS slips and the second annular pulley mechanism.[18] Preliminary testing was performed with increasing loads to ensure that tendon deformation did not occur at the input force of 142 N. The loading algorithm proceeded as follows: The FDS tendons were actuated with a force of 142 N directed through a clamp onto all 4 tendons; the FDP tendons were actuated through another clamp onto these 4 tendons using a force of 142 N; and the FDP and FDS tendons were actuated in combination with a force of 142 N acting on each clamp.

A calibrated Jamar dynamometer with the grip bar set at the second position was placed in the cadaver hand, and the reactive compression force was recorded for each trial of tendon tensioning. Gripping measurements were taken as the dynamometer was rotated within the cadaveric hand between a minimum of 15° and a maximum of 90°of dynamometer angulation (Figure 3). Six different positions were chosen, with each ultimately being self-selected by the cadaveric hand. Specifically, although the dynamometer was placed in iterations of approximately 15° once tendon tensioning proceeded, the dynamometer assumed a self-selected position that was slightly different (5°-10°) than initially positioned. This self-selected angulation was measured after grip measurements were recorded. Dr. Kaufmann took all the measurements with a handheld goniometer positioned between the compression axis of the dynamometer and the long axis of the second metacarpal bone, which was evident through the longitudinal wire. The compression axis of the dynamometer is in line with the movement of the handle toward the Jamar base. Intraexperimental measurement error was continuously identified as less than 5° through multiple angle measure-

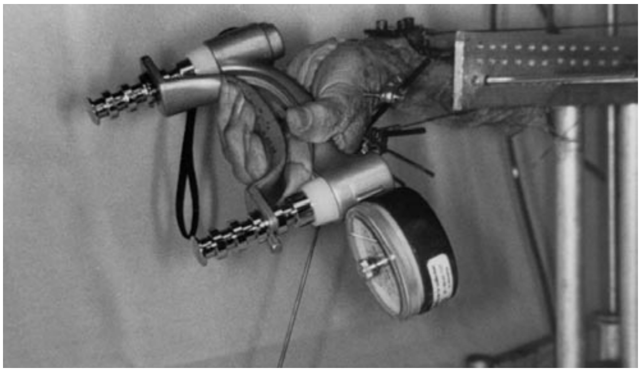

Figure 1. Experimental Setup. Cadaver hand holding dynamometer during grip testing.

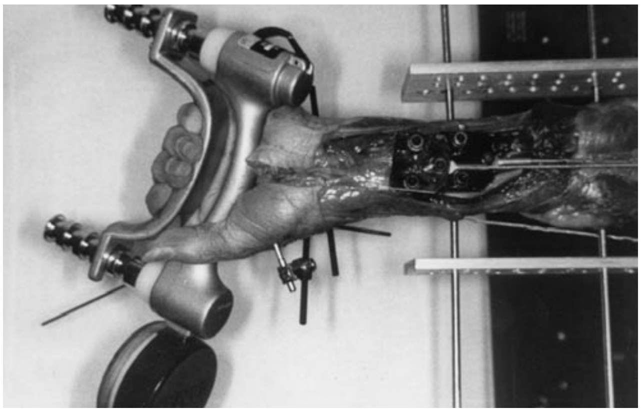

Figure 2. Experimental Setup. Flexor tendon actuation using FDP and FDS tensioning clamps.

Table. Grip-Strength Maxima and Corresponding Dynamometer Angulation for Different Modes of Hand Actuation

	Grip (kgf)	Angulation (°)	Grip (kgf)	Angulation (°)	Grip (kgf)	Angulation (°)
Tension mode (N)						
Flexor digitorum superficialis			142		142	
Flexor digitorum profundus	142				142	
Hand						
1	5.9	88	8.0	56	14.0	68
2	7.5	88	8.0	40	10.5	50
3	5.6	90	7.8	62	11.1	88
4	6.0	88	6.0	64	10.5	78
5	6.0	84	7.0	68	11.0	72
6	6.0	78	6.5	58	12.0	64
7	6.0	72	5.0	44	12.0	66
8	6.2	90	7.0	34	11.5	62
9	5.0	52	5.8	36	10.0	66
10	4.5	60	0	4.5	60	6.5
11	5.7	68	5.9	42	12.2	80
Mean	**5.9**	**78**	**6.7**	**51**	**11.4**	**68**
SD	**0.7**	**13**	**1.0**	**12**	**1.2**	**11**

ments between the dynamometer compression axis and the second metacarpal shaft axis.

Results

Eleven cadaveric forearms were tested, and each generated a data set of dynamometer angulation versus Jamar compression for the 3 modes of tendon tensioning. These data sets underwent constrained least squares quadratic regression to generate 3 force-versus-angulation curves for each specimen (Figure 3). Maximum dynamometer compression and corresponding angulation are listed in the Table. Testing of 11 cadaveric upper extremities showed the following properties across all specimens.

The FDP and FDS generated maximum compressive forces at different degrees of angulation ($P<.0001$). Mean angulation for maximum force during isolated FDS tensioning at 142 N was 51°. This angle corresponded to contact made between the middle phalanx and the dynamometer handle. Mean angulation for maximum force during isolated FDP tensioning at 142 N was 78°. This angle corresponded to contact made between the distal phalanx and the dynamometer handle.

The isolated FDP generated larger compressive forces with increasing angles, meaning with increasingly distal contact points between the finger and Jamar handle ($P<.0001$).

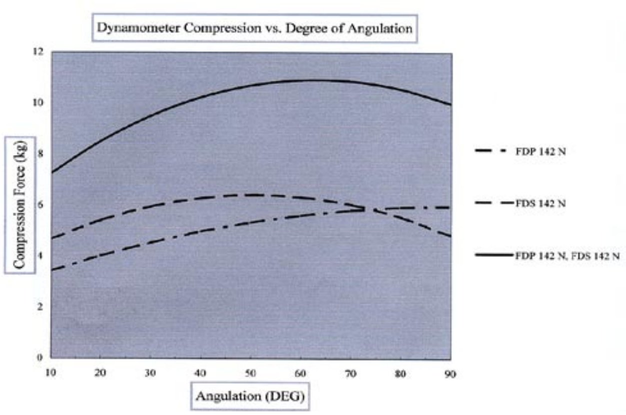

Figure 3. Compression force versus angulation curves representative of all 11 hands tested.

The isolated FDS was most effective when the handle was positioned at a smaller angle than the degrees of angulation that maximized the isolated FDP ($P<.0001$). For the FDS, there is initially a significant increase in grip strength as angle increases ($P<.01$) and also a significant tendency for grip strength to ultimately decline (as angle increases) after a maximum is reached ($P<.01$). The degrees that maximized FDS grip generation occurred when contact was made between the middle phalanx and the Jamar handle.

Combined FDP and FDS flexor tensioning was optimal at a dynamometer angulation located between the dynamometer angulation maximizing compression during isolated FDP and FDS tensioning. The combined actuation curves behave as a combination of isolated FDP and FDS curves. Mean angulation was 51° during isolated FDS tensioning and 78° during isolated FDP tensioning. During combined FDP and FDS tensioning, mean angulation for maximum compression force occurred at 68°. This angle corresponded to contact made between the DIP joint and the dynamometer handle.

There is no significant difference in gripping strength maxima generated by the isolated FDS when compared with the isolated FDP during equal tendon tensioning ($P>.05$). There is a tendency for the mean maximum gripping force during isolated FDP tensioning to be smaller than the mean maximum gripping force during isolated FDS tensioning.

When the FDP and FDS were simultaneously tensioned with 142 N, the resultant gripping strength maximum (11.4 kgf) was 10% less than the additive gripping strength maxima generated during isolated FDP (5.9 kgf) and FDS (6.7 kgf) tensioning at 142 N each.

Discussion

Cadaveric gripping motion was reproduced through actuation of the FDP and FDS tendon groups. Isolated tensioning of the FDP and FDS evaluated each muscle group; combined tensioning resembled in vivo gripping of the human hand without the

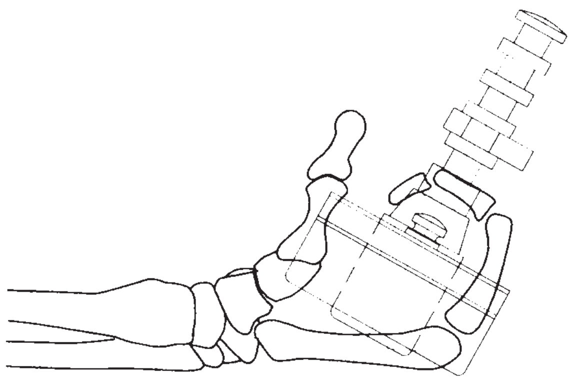

Figure 4. At smaller degrees of angulation, the flexor digitorum profundus tendon flexes the distal phalanx and generates side contact that exerts pressure perpendicular to the compression axis of the dynamometer.

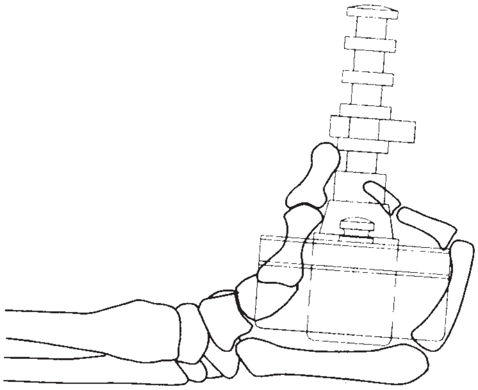

Figure 5. At larger degrees of angulation, the flexor digitorum superficialis cannot flex the distal interphalangeal joint and is limited in its ability to compress the dynamometer.

intrinsic muscle contribution. Actuation of the FDP and FDS tendons resulted in flexion of the wrist, MCP, and interphalangeal joints. The flexion moment created at the wrist was counteracted by a cable connected to an external fixator that rigidly positioned the wrist in 30° of extension. Tensioning reactive MCP and interphalangeal joint flexion was interrupted through placement of a Jamar dynamometer within the hand. This experimental design allowed the determination of grip strength from the actuated extrinsic flexor tendon(s).

Dynamometer rotation within the cadaveric hand resulted in different portions of the fingers contacting the dynamometer. Larger degrees of angulation yielded distal phalanx contact and increasingly smaller degrees of angulation resulted in middle and proximal phalanx contact with the handle. The finger-to-handle contact points directly influenced the unique gripping ability of the FDP and FDS tendons. The most efficient compression of an object within the hand is when it is positioned perpendicular to the bony structure compressing it. Otherwise, two force vectors are produced: one acting perpendicular, resulting in measurable dynamometer compression, and the other acting parallel to the dynamometer handle and bone. In our experiment, this latter shear force was readily apparent. It caused sliding of the handle within the cadaver hand. This motion occurred immediately after tendon tensioning but quickly ceased after the handle assumed a self-selected position. This self-selected position of the dynamometer allowed measurement of the angulation between the long axis of the second metacarpal and compression axis of the dynamometer.

Isolated actuation of the FDP or FDS generated maximal dynamometer compression at different degrees of angulation. The FDP grip was maximum at 78° compared with 51° for FDS grip. The larger degree of angulation during FDP tensioning correlated with the distal phalanges making contact with the dynamometer. The smaller degree of angulation, observed during FDS tensioning, correlated with the middle phalanges making contact with the dynamometer.

Isolated FDP actuation resulted in a continued increase in gripping strength as the finger-to-handle contact points moved from proximal to distal along the fingers. This increase in grip force is due to the FDP tendon reaching its maximum efficiency only when the distal phalanx contacts the dynamometer handle. At smaller degrees of dynamometer angulation (finger-to-handle contact at the middle phalanges), the FDP tendons flexed the distal phalanges until they made contact with the side of the dynamometer handle. This position prohibited the distal phalanges from exerting any compressive force to the dynamometer, and, therefore, the gripping force at lower degrees during isolated FDP actuation was less (Figure 4). At larger degrees of angulation, the FDP became more efficient as the distal phalangeal contact was able to generate force along the dynamometer compression axis.

Isolated actuation of the FDS was most effective when the dynamometer was positioned at smaller degrees of angulation corresponding to the middle phalanges being in contact with the handle. An initial increase in grip strength paralleled an increase in dynamometer angulation; however, a decrease in grip strength occurred as the dynamometer was rotated further and contacted the distal phalanges. At this point, reactive DIP joint extension occurred, promoting distal translation of the handle (Figure 5).

Similar gripping strength was generated during isolated FDP or FDS tendon tensioning at their respective optimal dynamometer positions with equal tensioning force. The physiologic cross-sectional area of the FDP is 1.43 times larger than the FDS, and its greater force-generation capability was not reproduced during equal tendon tensioning.[19] It is therefore likely that the FDP generates greater in vivo gripping strength.

Combined actuation of the FDP and FDS tendons yielded additional information. Maximum grip was attained at a mean angulation of 68°, which resides between the values determined for maximal gripping strength during isolated FDP and FDS actuation. The combined curve also integrated properties observed during isolated FDP and FDS actuation. Similar to the FDS curve, a maximal grip strength was obtained; this was followed by diminishment of grip strength during progressive angulation of the dynamometer. Similar to the FDP curve, maximal gripping force required some contact of the distal phalanges with the dynamometer. The maximum gripping strength was reached when finger-to-handle contact occurred at the level of the DIP joint. Not surprisingly, this contact point lies between the optimal site for FDP (distal phalanx) and FDS grip (middle phalanx).

The maximal gripping strength obtained during combined tensioning yielded a maximal gripping strength that was 10% less than the additive gripping strength maxima generated during isolated FDP and FDS tensioning. This is likely the result of neither the FDP nor the FDS functioning optimally. Specifically, the contact point that maximizes combined gripping strength is located between the points that maximize isolated gripping. Another cause may be FDS anatomy. FDS decussation has been described as a "Chinese finger trap" that tightens during its actuation[18] and may cause increased intertendinous friction that contributes to the decreased efficiency.

A limitation of this study is that intrinsic muscles that contribute to in vivo gripping were not actuated in this study. Another drawback is that, after tendon actuation, the dynamometer positioned itself in a self-selected position a few degrees differently than where it was positioned before tendon actuation. This process differs from the live situation, in which proprioceptive feedback may result in adaptive extrinsic or intrinsic force modulation that limits this phenomenon.

The determination of grip strength is a routine measure in clinical practice. The influence of dynamometer position has been demonstrated in this study and is an important consideration, particularly when evaluating gripping strength of the impaired hand with injuries to either the FDP or FDS tendons. In a patient without functional use of their FDP tendons, maximal gripping strength would be created when the dynamometer handle contacts the middle phalanges. In patients who cannot use their FDS tendons, maximal gripping strength is created when the dynamometer handle contacts the distal phalanges. Patients with normal FDP and FDS function should create maximal gripping force when the handle contacts the DIP joint region. Knowledge of the dynamometer position that will maximize the patient's ability to transmit force should be considered during grip measurements and rehabilitation and may allow for improved patient assessment.

Various conditions affect the capacity of the hand to generate grip, such as a low median or low ulnar nerve injury that results in an intrinsic muscle deficient hand. The resultant loss of grip strength is almost 50%, and the diminished dexterity impairs dynamometer manipulation within the hand.[20] Loss of tendon function may also impair grip-strength generation, mandating careful placement of the dynamometer, based on the aforementioned guidelines, in order to effectively record gripping strength.

Authors' Disclosure Statement

The authors report no actual or potential conflict of interest in relation to this article.

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