Importance of proximal A2 and A4 pulleys to maintaining kinematics in the hand: a biomechanical study

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Abstract

Purpose The A2 and A4 pulleys have been shown to be important in finger flexor tendon function. Other authors have suggested either reconstruction or venting of portions of these pulleys in an attempt to preserve finger function in certain clinical situations. This study examines the effects of partial incision of these pulleys on finger flexion kinematics and biomechanics.

Methods The index and ring fingers of 16 cadaveric hands were studied. The flexor digitorum profundus tendon was isolated and attached to a computer driven servo-motor. Micro-potentiometers measured flexion angles of the metacarpophalangeal, proximal inter-phalangeal and distal inter-phalangeal joints. Joint inertial torques were calculated making use of this experimental kinematic data.

Results Proximal 50 % incisions of either the A2 or the A4 pulleys resulted in a statistically significant decrease in overall finger motion. This effect was greatest in the proximal inter-phalangeal joint, with a decrease in joint motion, as well as an earlier time to initiation of motion. These changes in finger motion were more pronounced with A2 pulley incision than they were with A4 pulley incision, but the changes were

statistically significant in either case. No significant changes in joint inertial torques were shown.

Conclusions Our data provides evidence to the importance of the proximal portions of the A2 and A4 pulleys, and may support partial distal incision of these pulleys in certain clinical situations.

Keywords Biomechanics · Finger · Flexor tendon · Pulley excision · Range of motion

Introduction

The A2 and A4 pulleys have been shown to be important in finger flexor tendon function, and have been the focus of past studies [4–7, 10]. These pulleys are anatomically broad, covering a proportionately large area of the proximal and middle phalanx, respectively. Other authors have suggested either reconstruction or venting of portions of these pulleys in an attempt to preserve finger function when addressing a compromised underlying flexor tendon [4].

Finger kinematics, or finger motion, has been shown to be adversely affected by the amount of pulley that has been vented [2, 3, 8]. Mitsionis et al. [6] demonstrated the adverse kinematic effect of sacrificing 50 % or more of either A2 or A4 pulleys. Their study focused on venting these pulleys away from the proximal inter-phalangeal (PIP) joint, specifically the distal and proximal portions of the A2 and A4 pulleys, respectively. Their findings concluded that a minimal length of 50 % of either A2 or A4 pulleys must be maintained for optimal finger kinematics.

Anatomic location of pulley venting has also been shown to have an effect on finger function. Tanaka et al. demonstrated that venting the proximal portion of the A2 pulley increased peak tendon gliding resistance [9]. Their findings

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indicated that the anatomic location of the proximal A2 pulley was important to maintaining optimal tendon gliding.

Another biomechanical measure when dealing with finger function is that of inertial torque. Inertial torque is a calculated parameter that is extracted from motion data. It is a standard technique that is used in gait analysis to evaluate joint torques, resulting moments, and the associated resulting forces [1]. While this technique is well described in the biomechanical analysis of gait motion, to the best of our knowledge, it has not been applied to finger motion.

Accepting the minimal anatomic length of 50 % of the A2 and A4 pulleys for maintaining normal finger kinematics, and accepting the importance of the proximal portion of the A2 pulley in tendon gliding resistance, our aim was threefold: [6] to determine whether finger kinematics was influenced by the *location* of the 50 % venting of either the A2 or A4 pulleys, [5] to determine if the proximal portion of the A2 pulley was important both kinematically and biomechanically (via inertial torque calculation), and [4] to expand that knowledge to include the A4 pulley.

Materials and Methods

The index and ring fingers of 16 fresh-frozen human cadaver hands were studied in this experiment, totaling 32 fingers. The cadavers' ages varied widely from 40s to 80s, they were gender unbiased, and radiographs were obtained prior to the study to rule out arthritic changes. These fingers were divided into the following four trial groups: A2 proximal partial incision, A2 distal partial incision, A4 proximal partial incision, and A4 distal partial incision. Four hands were used in each trial group, totaling eight fingers (four index and four ring fingers) in each trial group (Fig. 1).

The specimens were thawed overnight to room temperature. Hands were isolated at mid-forearm, preserving all of the soft tissue distally. A standard zigzag incision was made on the palmar aspect of each index and ring finger to expose the flexor pulley system of those digits. This incision was made identically in all fingers, prior to data collection, and independent of whether the A2 or A4 pulley was being investigated. A volar incision was made in the distal forearm to isolate the flexor digitorum profundus (FDP) tendon. All incisions were left open during data collection to minimize potential error introduced by attempts at closure. Care was taken to preserve the palmar fascia, transverse carpal ligament, and distal volar forearm fascia. The remainder of the middle and ring fingers were preserved to maintain minimal soft tissue disruption in each hand (Fig. 2a).

Using a template guide, three 0.045 K-wires were inserted into the lateral aspect of each of the three finger joints: metacarpophalangeal (MCP), PIP, and distal inter-phalangeal (DIP). In each of these joints, one K-wire was inserted at the joint center of rotation, with an additional K-wire inserted into the bone proximal and distal to the joint. This provided a sturdy, reproducible mantle from which to measure. To these were attached three potentiometers (Honeywell Clarostat Model 586, www.electronic-parts.com) (Fig. 2b).

The specimen was attached to an experimental frame using two 5/64 Steinman pins: one transversely through the radius and ulna, and the other transversely through the proximal metacarpals (Fig. 2a). The specimen was attached volar side up and in neutral wrist flexion. The FDP tendon was sutured to a drive pulley attached to a servo motor (Fig. 3). Tendon excursion was provided by this computer driven servo motor. This allowed precise control of constant excursion force and velocity. Angular rotations of the MCP, PIP, and DIP joints were measured by voltage changes across the micro-potentiometers

Fig. 1 Experimental incision groupings — both index and ring fingers were used in each specimen. Remaining pulleys were left intact. *Dashed lines* indicate incisional end-points

Fig. 2 **a** Experimental setup. **b** Specimen setup

attached to each joint. Accuracy of angle measurement was found to be within $\pm 0.5^\circ$ experimentally with this setup. This was confirmed physically by using a goniometer to physically measure the angles after setup and immediately prior to running each trial.

The entire system was connected to a computerized data acquisition system, which recorded simultaneous voltage drops across all three potentiometers and saved the data for further processing. The starting point was measured at the initiation of motion, and this point varied with each finger as the tendons needed to pre-tension before movement began. This voltage data was filtered mathematically by

a computer, and converted to corresponding angles of rotation, resulting in a continuous recording of all joint positions (Fig. 3). The inertial torque of each joint was calculated in similar fashion. A 50 % partial incision of the pulley was performed in each finger, leaving the remaining pulley system intact. This process was then repeated with the partial incision.

Each of the trials utilized both the index and ring fingers. Each finger underwent two separate series with five recordings in each series. Measurements were initially taken of the finger with all pulleys intact; Series 1 examined this intact condition. Tendon excursion required to touch fingertip to palm was measured and recorded. The motor was then set to

Fig. 3 Experimental schematic

apply this standard amount of excursion for each recording, maintaining constant velocity and force. Micro-potentiometer voltages were tared to their corresponding joint angles. Each finger was flexed five times. The measurements were then repeated for the partial incision condition; Series 2 examined the partially excised pulley. The related pulley length was measured with calipers and recorded. Exactly 50 % of this was excised, keeping the remaining pulley system intact. Using the tendon excursion found experimentally in Series 1, the finger was again flexed five times.

Data Analysis

The resulting data was analyzed with a software program (coded in our lab using in C++, general programming language). This program incorporated a standard mathematical filter to eliminate ambient electrical noise and interference (MatLab numerical computing environment; The MathWorks, Inc., Natick, MA, USA).

Each series of trials was averaged to reduce random error in measurement. To do this, the angular measurements of each trial were analyzed to find experimental start and end points. The absolute changes in angles were used, as the potentiometers measure on a 360° arc which varies by setup and initial starting position. The end points were used to calibrate the system mathematically. The trials in each series were then averaged, and inertial torques were calculated based upon this data. This was done using a three-segment dynamic model and deriving the corresponding equations of motion mathematically. This is a standard technique used in gait analysis [1]. The final inertial torque and angular data was then plotted mathematically.

Finally, all data was transferred to SPSS (Predictive analytics software, SPSS Inc., Chicago, IL, USA) for statistical analysis. The data from the index fingers was compared to

that of the ring fingers. No difference in results or variability was noted.

Results

Representative plots for each trial are listed below. These plots portray the motion of each finger at each joint during a given excursion. Due to the anatomic and proportional variation between specimens, each series was compared to its related control. In other words, the motion of each finger with an experimentally cut pulley was plotted against its own un-cut motion. The greatest kinematic difference between these plots can be seen in the circumstances with proximal incisions of both A2 and A4 pulleys.

Overall, multiple variables were taken into account in the analysis of the data. These included: differences between the index and ring fingers, the earliest point of initiation of motion of the finger at any joint (initial range of motion [ROM]), the total ROM of the entire finger and of each of its joints, and the calculated inertial torques generated in each of these circumstances. Each of these variables was determined for the entire finger, as well as each joint: MCP, PIP, and DIP. Descriptive statistics are listed (Table 1).

For each of the trial circumstances, an analysis of variance (ANOVA) was conducted to determine if differences existed between the control plots and the experimental plots. Once a difference was determined, a Tukey post hoc test was conducted to determine where those differences occurred.

Partial A2 Pulley Incision

With respect to total finger motion (total ROM) and ROM at the PIP joint (PIP ROM), a significant difference was found in the location of A2 pulley incision when compared to controls

Table 1 Descriptive statistics

		Control		A2 proximal excision		A2 distal excision		A4 proximal excision		A4 Distal Excision	
		Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. Dev.
Initiation of motion (cm)	MCP	2.85	0.781	2.43	0.462	2.22	0.789	2.46	0.467	2.28	.850
	PIP	1.46	0.812	1.37	0.455	0.936	0.682	1.38	0.459	.961	.716
	DIP	1.64	0.620	2.18	0.454	1.81	0.887	2.21	0.458	1.83	.893
Individual joint ROM	MCP	51.8	3.39	49.3	1.78	49.6	0.707	48.3	1.74	49.8	.954
	PIP	79.8	1.89	73.3	3.34	77.4	1.51	71.8	3.27	77.6	1.81
	DIP	19.2	2.45	18.0	.876	17.6	2.97	17.6	0.858	17.4	2.90
Total finger ROM (°)		151	5.16	141	5.38	145	3.32	138	5.27	145	3.77
Joint inertia torque (kg cm ² /s ²)	MCP	0.079	0.0061	0.077	0.0017	0.083	0.0069	0.078	0.0017	.083	.0070
	PIP	0.057	0.0047	0.065	0.012	0.055	0.0074	0.066	0.012	.055	.0082
	DIP	0.019	0.00099	0.020	0.0011	0.020	0.00044	0.020	0.0011	.020	.00044

Fig. 4 Comparison of joint dynamics for A2 partial incision — uncompromised pulley dynamics for each hand are represented in *dotted lines*. Experimental results are represented in *solid lines*

(Fig. 4, Table 2). Incision of the proximal portion of the A2 pulley resulted in a greater decrease in ROM in both circumstances. Additionally, initiation of motion (initial ROM) at the PIP joint occurred earlier with proximal A2 pulley incision. With both total and initial ROM affected, A2 proximal incision was found to have the greatest influence at the PIP joint.

Incision of either proximal or distal A2 did not result in significant changes in motion at either the DIP or MCP joints.

Neither proximal nor distal A2 incision resulted in significant changes in inertial torque across any joints, when compared to controls.

Partial A4 Pulley Incision

With respect to total finger motion (total ROM) and ROM at the PIP joint (PIP ROM), a significant difference was found in the location of A4 pulley incision when compared to controls (Fig. 5, Table 3). Incision of the proximal portion of the A4 pulley resulted in a greater decrease in ROM in both circumstances. Additionally, initiation of motion (initial ROM) at the PIP joint occurred earlier with proximal A4 pulley incision. With both total and initial ROM affected, A4 proximal incision was found to have the greatest influence at the PIP joint. This is a similar, but less pronounced, result as that seen in proximal A2 pulley incision.

Incision of neither proximal nor distal A4 resulted in significant changes in motion at either the DIP or MCP joints.

Neither proximal nor distal A4 incision resulted in significant changes in inertial torque across any joints, when compared to controls.

Discussion

This study demonstrates the importance of the proximal portions of both the A2 and A4 pulleys to maintaining natural finger kinematics. Specifically, the PIP joint, which naturally has the greatest contribution to finger ROM, appears to be the most affected by alterations to the proximal A2 or A4 pulley systems. This is shown in the resulting earlier initiation of ROM about the PIP joint, as well as the marked decrease in total PIP motion. PIP flexion did not reach its maximum angular rotation in the study. The tendon of FDS and the intrinsic muscles contribute to normal flexion past 90°. This affect appears to be greater with A2 pulley incision than with A4 pulley incision. But angular rotation was more similar to uncut pulleys at MCP and DIP.

This effect may be partially explained by bowstringing. Tendon bowstringing, which occurs in the absence of a pulley, diminishes the angular rotation for a given excursion and increases the torque generated around involved joints. The flexor tendon pulley system prevents this, ensuring that adequate joint motion accompanies a given tendon excursion. This maintains system efficiency and lowers related forces.

Table 2 A2 related finger kinematic comparisons

	Initial ROM	Total ROM	MCP ROM	PIP ROM	DIP ROM
ANOVA: excision location vs. controls	32.754 $p=0.000$	11.019 $p=0.000$	1.398 $p=0.264$	18.956 $p=0.000$	1.096 $p=0.36$
Tukey post hoc test: proximal excision vs. control	$M=0.3751$ SD=0.1629	$M=0.0656$ SD=0.0202	—	$M=0.0783$ SD=0.0289	—
Tukey post hoc test: distal excision vs. control	$M=-0.1753$ SD=0.1316	$M=0.0249$ SD=0.0273	—	$M=0.0164$ SD=0.0152	—

Significant findings are presented in bold

Fig. 5 Comparison of joint dynamics for A4 partial incision — uncompromised pulley dynamics for each hand are represented in *dotted lines*. Experimental results are represented in *solid lines*

Theoretically, since the proximal portions of both A2 and A4 pulleys are anatomically near the MCP and PIP joints, respectively, it is possible that they are most vital to prevention of bowstringing around those joints. Thus, bowstringing should decrease joint motion across the entire digit, if not at these specific joints.

Although MCP ROM did not appear to be affected by proximal A2 pulley incision, our data clearly shows a decrease in overall finger flexion as a result. Despite the proximity, it appears that the PIP joint is the most sensitive to proximal removal of these pulleys.

With bowstringing, the decreased ROM should be accompanied by a related increase in torque. This study showed no significant change in inertial torque with respect to pulley resection. While it is possible that another mechanism is contributing to these findings, it is also possible that the resultant changes in torque are too small to be measured with our present study size. Future work with a larger sample size would be necessary to further examine this.

Additionally, our data shows that initiation of ROM at the PIP joint is earlier with the lack of proximal A2 or A4 pulleys. This effect is coupled with a short increased velocity of PIP motion after the motion is initiated. This may be due to decreased local friction due to partial removal of the pulley system at the proximal sections. However, this effect was not seen when the distal pulleys were excised. Further research is

necessary to determine the underlying causes of this phenomenon, and whether it is clinically significant.

We believe that all structures in the hand flexor system may affect the biomechanics of the hand. Because the index and ring fingers are most proportionately similar, these fingers were used in our study design. This effectively doubled our sample size, while keeping a large portion of the hand intact. However, we acknowledge that there may be subtle biomechanical differences between the individual digits of the same hand. Further work is necessary to determine whether such subtleties exist.

The FDS tendon was not controlled for, as only the FDP tendon crosses the MCP, PIP, and DIP joints and contributes to bowstringing across all three of these joints. The FDS tendon is very important in finger flexion, but it was not the focus of this paper. Future work includes addressing the role of the FDS tendon.

Additionally, our study design is consistent with that of prior work in that it does not include the pull of the intrinsic musculature in the hand. To the best of our knowledge, there is no simple way to address intrinsic pull in a cadaver model without violating much of the surrounding anatomy. While this may be a shortcoming of cadaver models in general, we feel that our findings are relevant despite being a non-physiologic circumstance. Further work must be done to determine this.

Table 3 A4 related finger kinematic comparisons

	Initial ROM	Total ROM	MCP ROM	PIP ROM	DIP ROM
ANOVA: excision location vs. controls	32.754 $p=0.000$	11.019 $p=0.000$	0.514 $p=0.676$	18.956 $p=0.000$	0.015 $p=0.997$
Tukey post hoc test: proximal excision vs. control	$M=0.3374$ SD=0.1679	$M=0.1022$ SD=0.0194	—	$M=0.1145$ SD=0.0278	—
Tukey post hoc test: distal excision vs. control	$M=-0.1947$ SD=0.1426	$M=0.0395$ SD=0.0246	—	$M=0.0305$ SD=0.0369	—

Significant findings are presented in bold

As with any anatomical structure, no two hands are identical and we fully acknowledge the potential effect of inter-specimen variability in our study (which can be seen by comparing the control plots of our results of any one hand to another). Our study design accommodated this variability by comparing each hand to itself. Only the behaviors from those direct comparisons were related between specimens. The behaviors of the dynamic responses would not be affected by inter-specimen variability, and are thus comparable. The focus of our study was to relate those trends seen in specific specimen. In order to compare biomechanical trends among specimen, data resolution must be sacrificed and a biomechanically significant plot must be established, which would require a large sample size. This is grounds for future work.

Possible clinical correlations of this paper include distal venting of the A2 and A4 pulleys in a surgical setting. But this study is not clinical in nature and does not address the additional roles of the FDS tendon and intrinsic muscles of the hand.

In conclusion, our data provides evidence to the importance of the proximal portions of the A2 and A4 pulleys, and may support partial distal incision of these pulleys in certain clinical situations.

Conflict of interest F. Amirouche, B. Chow, J. C. Chow, M. Gonzalez, D. McNeal, and J. Sensinger have no conflict related to the content of this study.

Statement of human and animal rights This study was approved by the Human Research Committee at our institution. Verbal consent was not applicable to this study.

Statement of informed consent Informed consent was not applicable to this study.

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This article does not contain any studies with human or animal subjects.