SCIENTIFIC ARTICLE

The Effect of Intrinsic Loading and Reconstruction Upon Grip Capacity and Finger Extension Kinematics

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Purpose To compare active and passive reconstructive procedures for tetraplegia and their ability to produce a powerful grip and allow appropriate finger extension in a cadaveric model.

Methods Seventeen fresh-frozen hands were used, which included 5 in intrinsic minus and intrinsic activation conditions, 6 with Zancolli-lasso tenodeses, and 6 with modified House tenodeses to simulate intrinsic function. To test grip, flexor digitorum profundus tendons were powered with a motor. Polyvinyl chloride cylinders of diameters 43, 51, 57, 70, or 89 mm and masses 250, 400, or 550 g were used. Grip was considered successful if the cylinder was grasped and resisted gravity. Finger extension was tested by powering the extensor tendons in the same hands.

Results No successful grasps were recorded in the intrinsic minus hands for larger diameter cylinders ($\geq$70 mm), whereas multiple successes were seen after intrinsic activation and after Zancolli-lasso and House procedures. Whereas active intrinsic and the House reconstruction reached near full extension, this was not true for the Zancolli-lasso group.

Conclusions These data demonstrated that active and passive intrinsic reconstruction methods improved basic grasp and release kinematics in experimental cadaver hand models. Using our model and based on the more optimal kinematics and full extension of the House procedure, we suggest that this should be the preferred tenodesis-based intrinsic reconstruction method. Nevertheless, both procedures were equally successful at grasping objects of the sizes and masses studied.

Clinical relevance Comparative clinical studies are indicated to corroborate the findings of this cadaveric hand model. *(J Hand Surg Am. 2015;40(1):96–101. Copyright © 2015 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words House procedure, intrinsic balancing, reconstructive hand surgery, tetraplegia, Zancolli-lasso procedure.

Additional material is available online.

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Received for publication May 9, 2014; accepted in revised form September 5, 2014.

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

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0363-5023/15/4001-0017$36.00/0
http://dx.doi.org/10.1016/j.jhsa.2014.09.031

SPINAL CORD INJURY AFFECTS between 250,000 and 500,000 new individuals per year worldwide.[1] Restoration of upper extremity function ranks as the number one priority among spinal cord–injured tetraplegic patients, far surpassing other needs.[2] One of the major challenges in surgical reconstruction in tetraplegia is creating function in the face of a lack of available active donor muscles to power hand function. In such cases, tenodesis procedures, such as the Zancolli-lasso procedure and the modified House procedure, may be used. Both procedures simulate

TABLE 1. Criteria for Functional Success in the Cadaveric Model

	Hand Condition			
Criterion	Intrinsic Minus	Intrinsic Active	House	Zancolli
Finger extension				
Delayed MCP extension	−	+	+	−
Full finger extension to neutral	+	+	+	−
Finger flexion				
Early MCP flexion	−	+	+	−
Broad-sweeping motion*	−	+	+	+
Full finger flexion into palm	+	+	+	+

Note that only the House procedure hands resemble the actively INT loaded hands across all criteria. MCP, metacarpophalangeal; INT, instrinsic.
*The Zancolli-lasso procedure achieves broad-sweeping motion by its pre-flexion of MCP, not by a kinematic advantage.[7]

sagittal plane function of the intrinsic musculature,[3–5] coupling metacarpophalangeal (MCP) joint flexion and interphalangeal (IP) joint extension.[6,7] This allows for a broad sweeping grasp more conducive to the fingers closing around objects.

Nevertheless, restoration of proper flexion kinematics by reconstructive surgery, although obtainable, is not necessarily functional. Truly functional grip also requires appropriate digital extension to open the palm to accept an object and then sufficient finger flexion to secure objects that may vary in size and mass (Table 1).

Intrinsic muscles function not only in finger flexion as described, but in extension as well, acting to extend the IP joints with the MCP joint flexed.[8,9] We therefore propose two functional criteria—sufficient opening and sufficient grip—as the mechanical test of a successful intrinsic reconstructive procedure. The purpose of this study was to determine the relationship of active or passive intrinsic reconstruction on grip ability (defined as the ability to grip cylinders of increasing diameter and mass) and on the kinematics of finger extension.

METHODS

Sample preparation

Seventeen fresh-frozen hands were used for this experiment, with their normal and reconstructed kinematics reported previously.[6,7] These included five non-reconstructed hands (3 male, 2 female; average age, 75 y; range, 59−88 y), 6 modified House procedure reconstructed hands (6 female; average age, 86 y; range, 84−89 y), and 6 Zancolli-lasso procedure reconstructed hands (6 female; average age, 87 y; range, 80−94 y). No major joint contractures were noted pre-experimentation. The House and Zancolli-lasso procedures were performed as previously reported.[3−5,10,11] An experienced reconstructive hand surgeon performed all reconstructions.

Briefly, for House hands, a flexor digitorum superficialis (FDS) tendon graft was sutured to the radial lateral and central bands of the index finger, passed proximally beneath the insertion of the first dorsal interosseus such that it remained palmar to the MCP joint axis of rotation, directed under the extensor digitorum communis index and extensor indicis proprius tendons dorsally proximal to the MCP joint, and passed back distally through the lumbrical tunnel of the middle finger and sutured to the radial lateral and central bands of the middle finger. A second graft was sutured in an analogous fashion to the radial lateral bands of the ring and small fingers. For Zancolli-lasso hands, FDS tendons were identified and cut distal to the A1 pulley and sutured back to themselves proximally, thus creating a lasso about the A1 pulley.

Hand preparation was as follows. All flexor digitorum profundus (FDP) and extensor digitorum communis (EDC) tendons were individually sutured proximally with 2-0 silk. Where there was a scarce contribution of EDC to the small finger, the extensor digiti minimi was used instead. Due to their identical action in the sagittal plane, lumbricals and interossei were considered together and will be referred to simply as the intrinsics. Intrinsic action was simulated by suturing with 2-0 silk into the tendinous insertion of each lumbrical to the radial lateral band of the extensor mechanism. All palmar carpal ligaments were left intact, and volar tendons with affixed sutures were passed proximally through the carpal canal. Each thumb was amputated at the level of the MCP joint to facilitate video capture of finger motion.

We note that this cadaveric model did not necessarily reproduce the complexities of true hand function but was an experimental model used to isolate intrinsic functional effects.

Grip comparison experimental design

Two Schanz pins were drilled into each hand dorsally at the base of the third metacarpal. These secured the hand in a position simulating neutral forearm rotation, with the palmar creases oriented vertically. FDP sutures were affixed proximally to a dual-mode servo-motor (Aurora Scientific, Model 310, Aurora Inc., Ontario, Canada), and the EDC was statically loaded to 50 g to simulate passive muscle resistance. For non-reconstructed hands, experiments were performed once with the intrinsics unloaded (0 g) and again with the intrinsics loaded (500 g, which significantly alters the kinematics of finger flexion).[6] For Zancolli-lasso hands, FDS tendons were anchored proximally, representing their origin from the elbow, to provide MCP joint flexion of 40°. Thus, these hands began with a pre-flexion of 40° at the MCP joint, which, in our clinical experience, is the most common postoperative position of these hands with the wrist at a neutral-to-slightly-extended position (position of function) and is kinematically similar to alternative degrees of MCP pre-flexion.[7]

Cylinders of various diameter and mass were placed directly in the middle of the palm of each hand. Diameters were 43, 51, 57, 70, and 89 mm, whose values center roughly around the diameter of a typical 12-ounce soda can (66 mm). Masses were 250, 400, and 550 g, which center roughly around the mass of a full 12-ounce (390 g) soda can. Cylinders were polyvinyl chloride with no modification to their surface that would enhance grasp. The motor-affixed FDP tendons were then displaced up to 50 mm with the object placed on a tabletop. This was the minimal excursion of FDP to provide full finger closure in all experimental hands and thus represents a best-case clinical scenario across all experimental conditions. Then, after the grasp, the tabletop was removed. If the fingers wrapped around the cylinder and successfully gripped it after the tabletop was removed, this was considered a success. If the fingers either pushed the cylinder away during roll-up finger flexion or failed to maintain grip after the tabletop was removed, this was considered a failure.

Finger extension experimental design

Finger extension experiments were performed similarly to previous grasp experiments involving non-reconstructed, House, and Zancolli-lasso hands,[6,7] with the modification that hands were positioned palm-down and EDC was affixed to the motor while FDP was passively tensioned with a load of 250 g (Fig. 1). This mass allowed optimal finger motion from closed fist to open hand. Thus, fingers began in flexion into the palm and subsequently extended with motor movement. In non-reconstructed hands, intrinsic sutures were passively tensioned with variable loads (0, 125, 250, 375, or 500 g), simulating varying degrees of intrinsic activation. For Zancolli-lasso hands, FDS tendons were again tensioned to provide MCP joint flexion of 40°. They were then anchored proximally to simulate the origin of that muscle from the elbow and maintain that degree of MCP joint flexion during motor-powered finger extension. As stated earlier, this has been our clinical experience for the position of this joint postoperatively in these patients with wrist at a position of function. Kirschner wires were drilled into the middle finger metacarpal and phalanges to serve as markers. Only one digit was analyzed, as previous work showed no effect of finger type on sagittal plane kinematic properties.[6,7] The middle finger was chosen because the plane of motion of this digit was most consistently orthogonal to the optical plane of our camera. Movement was video-captured from the radial side of the hand and digitized in MATLAB (The Mathworks, Natick, MA).

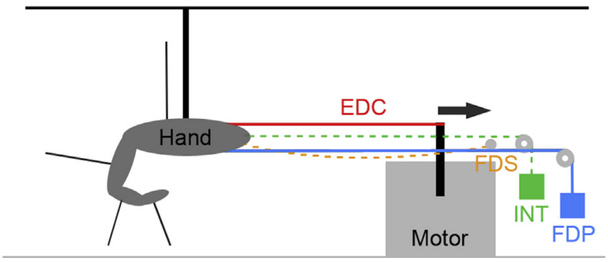

FIGURE 1: Experimental setup for motor-powered finger extension. EDC tendons (red) affixed to motor. FDP (blue) affixed to 250 g static force simulating passive resistance. In non-reconstructed hands only, the intrinsic sutures (INT, green dotted line) were affixed to a static force of 0, 125, 250, 375, or 500 g. In Zancolli-lasso hands only, FDS (orange dotted line) sutures were anchored proximally to provide MCP flexion of 40°. House procedure hands had no additional attachments.

For data analysis, we initially looked at the joint angle of any given joint as a function of EDC excursion. The derivative of this curve provided the slope at any given point. Where this was maximal, the joint was extending most quickly. We termed this the point of maximal angular change for each joint (MCP, proximal interphalangeal [PIP], distal interphalangeal [DIP]) and used it as a surrogate to represent the relative order of joint extension. For example, if the

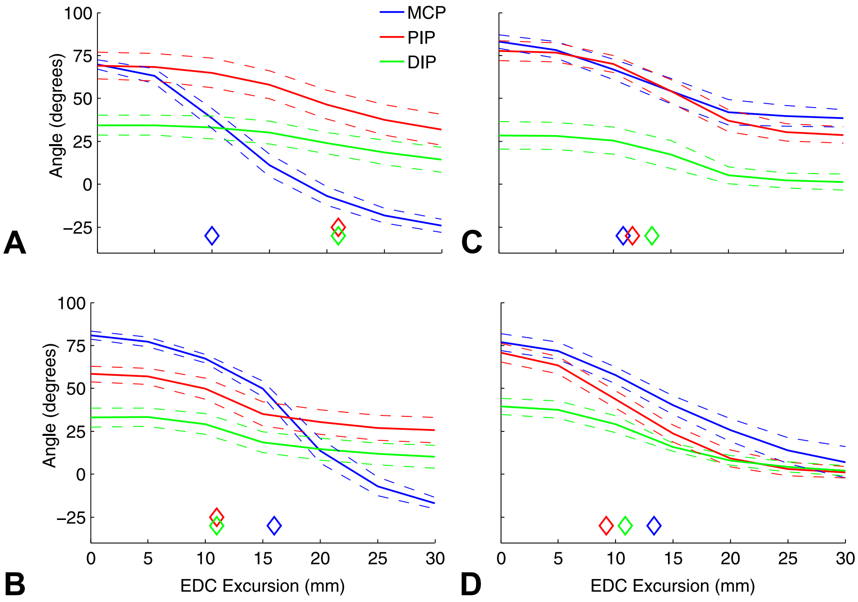

FIGURE 2: Angle of the MCP, PIP, and DIP joints as a function of EDC excursion. **A** Intrinsically unloaded hands (N = 5). **B** Intrinsically loaded (500 g) hands (N = 5). **C** Zancolli-lasso procedure reconstructed hands (N = 6). **D** House procedure reconstructed hands (N = 6). In the absence of intrinsic load, MCP joint extension precedes IP joint extension (see diamonds), whereas when intrinsically loaded, IP joint extension precedes MCP joint extension. Means (—) and standard errors (- -) are shown. ◇ = excursion of EDC tendon where maximum rate of extension occurred for each joint.

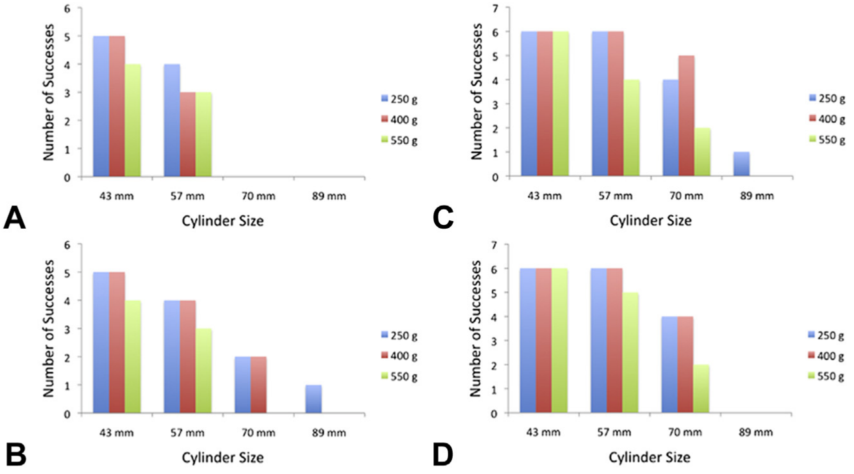

FIGURE 3: Graphical representation of success of hands gripping cylinders of varying diameters and masses. **A** Intrinsically unloaded hands (N = 5). **B** Intrinsically loaded (500 g) hands (N = 5). **C** Zancolli-lasso procedure reconstructed hands (N = 6). **D** House procedure reconstructed hands (N = 6). Note the beneficial effects of either active intrinsic loading or surgical reconstruction.

point of maximal angular change of MCP occurred at 15 mm EDC excursion and the point of maximal angular change of PIP occurred at 25 mm EDC excursion, the MCP joint was said to extend before the PIP joint. (These plots with their respective points of maximal angular change are best visually portrayed in our results shown subsequently in Fig. 2). A two-way analysis of variance (ANOVA) with repeated measures compared the effect of intrinsic load on joint kinematics. Factors were intrinsic load (0, 125, 250, 375, 500 g) and joint (MCP, PIP, DIP). A second two-way ANOVA with repeated measures compared the effect of reconstructive procedure on joint kinematics. Selected factors were procedure (House, Zancolli-lasso) and joint (MCP, PIP, DIP). Statistical significance (α) was set at .05.

RESULTS

Comparison of grip capacity

There were differences among groups in their ability to grasp objects of varying diameter and mass. In general, there were fewer successes as object diameter or object mass increased (Fig. 3). Clearly, intrinsic loading increased the number of grasp successes compared with the intrinsic minus hand. Specifically, no successes were recorded with the intrinsic minus hands at the 70 and 89 mm diameter size (Fig. 3A), whereas multiple such successes were seen after active intrinsic loading (Fig. 3B). The actual mode of failure also varied slightly as a function of intrinsic reconstruction; namely, at heavier masses, intrinsic-activated hands were more likely to surround the cylinder but failed by an inability to maintain grip against gravity, whereas intrinsic minus hands were more likely to fail by roll-up flexion pushing the cylinder away (see Appendix A, available on the *Journal's* Web site at www.jhandsurg.org). In terms of grasp successes, no difference was observed between the two reconstructive procedures. Both the Zancolli-lasso (Fig. 3C) and House (2D) procedures increased the size of the object that could be grasped, supporting the idea that reconstruction by tenodesis creates sufficient grip capacity without an active transfer (Table 1).

Finger extension

In contrast to grip success, the intrinsic powering or reconstruction method had a profound effect on the ability to open the hand by EDC excursion. Intrinsic activation changed the order of joint extension significantly ($P < .001$). For example, at an intrinsic load of 0 g (Fig. 2A), extension occurred early in the MCP joint (13 ± 0 mm of EDC excursion) and later in the PIP joint (24 ± 2 mm) and DIP joint (24 ± 2 mm), whereas after powering (Fig. 2B), extension occurred earlier in the PIP joint (14 ± 1 mm) and DIP joint (14 ± 1 mm) and later in the MCP joint (19 ± 1 mm).

The intrinsic-activated order of joint extension, from PIP and DIP joints to MCP joint, was not restored by the Zancolli-lasso hands (Fig. 2C), which resembled an intrinsic-unloaded scenario. Specifically, these hands demonstrated early MCP extension (13 ± 1 mm) compared with the PIP joint (14 ± 1 mm) and DIP joint (16 ± 2 mm), whereas the House hands (Fig. 2D) resembled the intrinsic-activated scenario with joint extension from the PIP joint (12 ± 2 mm) and DIP joint (13 ± 1 mm) to the MCP joint (16 ± 3 mm). The difference between these two procedures, as indicated by the two-way ANOVA interacted term, approached but did not reach significance ($P = .1$, Fig. 2). Similarly, the final position of the fingers at full extension varied between the two reconstruction methods. Whereas the House group reached near full extension with final joint positions of the MCP joint 7 ± 9, PIP joint 1 ± 4, and DIP joint 2 ± 3 (degrees flexion ± SE), the Zancolli-lasso group failed to reach full extension, with final positions of MCP joint 38 ± 5, PIP joint 29 ± 5, and DIP joint 1 ± 5. This resulted in a fingertip position for the Zancolli-lasso reconstruction that was substantially different from the House procedure (Fig. 4). Thus, using the criteria of magnitude of joint extension and order of joint extension, the House procedure produced a more satisfactory result (Table 1).

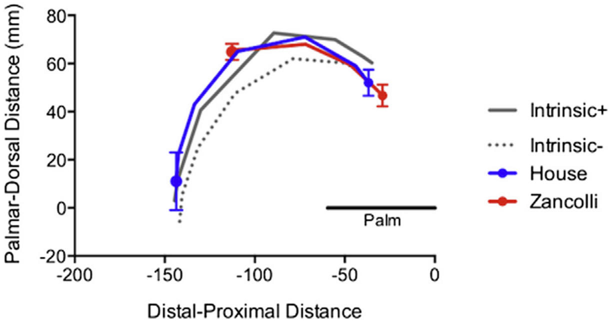

FIGURE 4: Path of the middle fingertip during extension for four conditions. The coordinate system is shown for a hand with the palm facing up with the origin at 0,0. Thus, a fully extended finger reaches a palmar-dorsal distance of near zero. Note that the intrinsic minus hand (dotted line) traverses a smaller arc compared with other conditions because the MCP joint is extended very early in extension (cf Fig. 2) compared with the intrinsically activated hand (solid gray line). House reconstruction (blue) closely mimics the intrinsic plus hand whereas Zancolli-lasso reconstruction fails to fully extend the fingertip due to inadequate MCP and PIP joint extension. Standard error bars are shown only for the starting and final positions of the reconstructed hands for clarity.

DISCUSSION

The purpose of this study was to quantify the functional effects of intrinsic powering as well as to compare two tenodeses commonly used for intrinsic reconstruction. We found that active powering of the intrinsic function significantly enhanced hand function as indicated by ability to grasp and hold larger objects. In addition, the House procedure produced superior results to the Zancolli-lasso procedure when considering a combination of functional criteria (Table 1).

Powering of the intrinsics either by simulated tendon transfer or by tenodesis permitted grip of objects larger than ~70 mm (Fig. 3). This was specifically due to grasp characterized by simultaneous PIP joint extension and MCP joint flexion, thereby avoiding finger roll-up, which simply pushed the object out of the hand rather than encircling it (Appendix A). Although both House and Zancolli-lasso procedures produced grip capacity comparable to active intrinsic loading in terms of cylinder size, we do not believe that they provided identical functional grasp. This is because the Zancolli-lasso procedure, which creates a minimum MCP joint flexion angle of about 40°, results in a more closed hand that must be navigated around the object to be grasped. In our grip test, we simply bypassed this issue by placing the object directly into the palm. In practice, a patient would have to compensate to correctly place the hand relative to the object.

We showed previously that intrinsic loading alters the order of finger joint motion whereby, with the intrinsic loaded hand, MCP joint flexion precedes IP joint flexion while the intrinsic minus hand demonstrates IP joint flexion followed by MCP joint flexion.[6] In this regard, the House procedure resulted in a better approximation of the intrinsic-loaded hand, and the Zancolli-lasso reconstruction resembled an intrinsic minus hand.[7] Here, we show that that pattern applies to finger extension as well, though in the present study this order effect only approached statistical significance ($P = .1$).

Powering intrinsic muscles directly or by tenodesis augments IP joint extension. Although both reconstructive methods permitted finger extension, the Zancolli-lasso procedure, with its fixed MCP joint flexion angle of about 40°, resulted in a greatly diminished MCP joint extension trajectory (Fig. 2C) and significantly different ending position of the fingertips (Fig. 4, large circles). Although this MCP joint angle was a direct result of our experimental design to simulate a clinical finding, the PIP angle of 29° ± 5° was not. As a result, *in vivo* it would likely be necessary to navigate the Zancolli-lasso hands around a cylinder in order to accept the objects. For this reason, although restoration of finger extension is not a primary goal of intrinsic tenodesis, we prefer the House tenodesis as the fingers are potentially fully extendable and have angular trajectories and final fingertip position that is indistinguishable from an actively reconstructed hand. Note, however, that whereas the cadaver hands showed no evidence of PIP joint pathology, a Bouvier test was not performed. Therefore, we cannot ensure that full IP joint extension would have been possible with our experimental MCP joint flexion angle in the Zancolli hands. This is a weakness of our study. *In vivo*, this may have precluded these hands from candidacy for a Zancolli-lasso procedure, making the House reconstruction more favorable. Likewise, no Bunnell test was performed, but there was no evidence of intrinsic tightness in any of the hands.

This study has several additional limitations. As a cadaveric study, it fails to simulate the added complexity of these procedures *in vivo*, such as postoperative adhesions and joint stiffness. Future studies would be required to assess whether our findings hold up clinically. Although a previous clinical study failed to show a difference in grip strength or activities of daily living between the two procedures,[5] it did not address finger kinematics or the ability to grasp objects of increasing size, which was the focus of the present study. A further potential limitation is that the Zancolli-lasso procedure relies on passive resistance of both the FDS tendon and muscle belly, which may provide increased elasticity in comparison with the tendon alone, as simulated in the present study. The 40° MCP flexion attained postoperatively with the wrist in neutral position, and simulated in our Zancolli-lasso hands, is the experience of our senior surgeon, is not published in the literature, and may not be the experience of others.

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APPENDIX A. Grip Success Tally for All 4 Hand Conditions

Unreconstructed hands (INT = 0 g):

	M1 = 250 g			M2 = 400 g			M3 = 550 g		
	S	F(s)	F(p)	S	F(s)	F(p)	S	F(s)	F(p)
S1 = 43 mm	5	0	0	5	0	0	4	1	0
S2 = 51 mm	4	0	1	4	0	1	4	0	1
S3 = 57 mm	4	0	1	3	1	1	3	1	1
S4 = 70 mm	0	0	5	0	0	5	0	0	5
S5 = 89 mm	0	0	5	0	0	5	0	0	5

Unreconstructed hands (INT = 500 g):

	M1 = 250 g			M2 = 400 g			M3 = 550 g		
	S	F(s)	F(p)	S	F(s)	F(p)	S	F(s)	F(p)
S1 = 43 mm	5	0	0	5	0	0	4	1	0
S2 = 51 mm	5	0	0	5	0	0	5	0	0
S3 = 57 mm	4	0	1	4	0	1	3	1	1
S4 = 70 mm	2	1	2	2	1	2	0	3	2
S5 = 89 mm	1	0	4	0	1	4	0	1	4

House reconstructed hands:

	M1 = 250 g			M2 = 400 g			M3 = 550 g		
	S	F(s)	F(p)	S	F(s)	F(p)	S	F(s)	F(p)
S1 = 43 mm	6	0	0	6	0	0	6	0	0
S2 = 51 mm	6	0	0	6	0	0	6	0	0
S3 = 57 mm	6	0	0	6	0	0	5	1	0
S4 = 70 mm	4	1	1	4	1	1	2	2	2
S5 = 89 mm	0	1	5	0	3	3	0	2	4

Zancolli-lasso reconstructed hands:

	M1 = 250 g			M2 = 400 g			M3 = 550 g		
	S	F(s)	F(p)	S	F(s)	F(p)	S	F(s)	F(p)
S1 = 43 mm	6	0	0	6	0	0	6	0	0
S2 = 51 mm	6	0	0	6	0	0	6	0	0
S3 = 57 mm	6	0	0	6	0	0	4	2	0
S4 = 70 mm	4	0	2	5	0	1	2	3	1
S5 = 89 mm	1	0	5	0	1	5	0	3	3

Cylinder diameters stratified by row. Cylinder masses are stratified by column. Success versus failure stratified by sub-column. S, success; F(s), failure by cylinder slipping out of grip against gravity; F(p), failure by fingers pushing cylinder away due to roll-up flexion; INT, intrinsic loading; S#, sample; M, mass.