Intrinsic Hand Muscle Function, Part 2: Kinematic Comparison of 2 Reconstructive Procedures

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Purpose  Reconstruction of grasp is a high priority for tetraplegic patients. Restoration of finger flexion by surgical activation of flexor digitorum profundus can result in roll-up finger flexion, interphalangeal (IP) joint before metacarpophalangeal (MCP) joint flexion, which can be improved by restoring intrinsic function. This study compares grasp kinematics between 2 intrinsic balancing procedures—Zancolli-lasso and House.

Methods  The intrinsic muscles of 12 cadaver hands were reconstructed by either the Zancolli-lasso or the House procedure (n = 6 each) and tested by deforming the flexor digitorum profundus (FDP) with a motor to simulate hand closure. Results were compared with 5 control hands. All 17 hands were studied by video analysis. Kinematics were characterized by the order of MCP joint and IP joint flexion. Optimal grasp was defined as the maximal fingertip-to-palm distance during the arc of finger closure.

Results  Kinematics differed between the 2 procedures. The Zancolli-lasso reconstructed hands flexed first in the IP joints, and then in MCP joints, resembling an unreconstructed intrinsic-minus hand whereas the House reconstructed hands flexed first in the MCP joints and then in the IP joints, resembling an intrinsic-activated hand. Maximal fingertip-to-palm distance did not differ significantly between the 2 procedures, and both showed improvement over unreconstructed controls.

Conclusions  Both intrinsic balancing techniques improved grasp. Only the House procedure restored hand kinematics approximating those of an intrinsic-activated hand. Improvement in fingertip-to-palm distance in Zancolli-lasso hands resulted primarily from the initial resting MCP joint flexion of 40°. We therefore advocate the more physiological House procedure for restoration of intrinsic function in tetraplegic patients.

Clinical relevance  This study provides a rationale for advocacy of 1 reconstructive procedure over another. (J Hand Surg 2013;38A:2100–2105. Copyright © 2013 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.
S P I N A L C O R D I N J U R Y IS A life-altering event for any patient. When tetraplegia results, the loss of functional independence can be devastating. Worldwide, the incidence of spinal cord injury is 10 to 80 per million individuals each year, with roughly one third of those injuries resulting in tetraplegia. In a survey of tetraplegic patients, 49% ranked reconstitution of hand/arm function as their number 1 priority in rehabilitation, with no other priority surpassing 13%. Despite this fact, surgical reconstructions of the upper extremity remain underperformed as a whole. In the United States, despite over 100,000 citizens living with tetraplegia, less than 400 upper extremity reconstructive procedures are performed each year.

Finger flexion can often be restored by tendon transfer to activate the flexor digitorum profundus (FDP). However, this transfer may result in roll-up finger flexion—interphalangeal (IP) joint before metacarpophalangeal (MCP) joint flexion—because most tetraplegic patients lack intrinsic muscle function. Although the extrinsic flexors provide concurrent flexion of the MCP and IP joints, the intrinsic muscles couple MCP joint flexion with IP joint extension. This coupling delays IP directed under the extensor digitorum communis remained palmar to the MCP joint axis of rotation, fixation of the first dorsal interosseous such that it remained palmar to the MCP joint axis of rotation, directed under the extensor digitorum communis index and the extensor indicis proprius tendons proximal to the MCP joint. Another slip of the tendon passed distally through the lumbrical tunnel of the middle finger palmar to the intermetacarpal ligament, and sutured to the radial lateral and central bands of the middle finger with 3-0 suture with the MCP joint held in a flexed position. A second tendon was sutured in an identical fashion to the radial lateral bands of the ring and little fingers.

After reconstruction, hands were amputated at the radiocarpal joint. The thumb was amputated at the MCP joint so as not to obscure video recording. FDP tendons were identified proximal to the carpal tunnel, and the ends were individually sutured proximally with 2-0 suture. The palmar carpal ligament remained intact. The extensor digitorum communis tendons were sutured individually at the level of the wrist with 2-0 suture. Owing to the scarce contribution of the extensor digitorum communis to the extensor apparatus of the little finger in most hands, the extensor digiti minimi tendon was the substituted recipient of the graft.

Zancolli-lasso reconstructed hands

Another 6 fresh-frozen hands (6 female; average age, 87 y; range, 80–94 y) were reconstructed using the Zancolli-lasso procedure (Fig. 2). Briefly, incisions were made over the palmar aspect of each MCP joint. Each FDS tendon was identified and cut distal to the A1 pulley. The proximal end was sutured to itself proximally with 3-0 suture, thus lassoing the A1 pulley. The MCP joint was held in a flexed position during this tightening, and all fingers were balanced relative to each other to secure a normal cascade. After reconstruction, hands were dissected and prepared similarly to the House hands. In addition, FDS tendons were identified proximal to the carpal tunnel and sutured en masse at their ends with 2 sutures. All reconstructions were performed by an experienced hand surgeon (J.F.).

MATERIALS AND METHODS

Modified House reconstructed hands

Six fresh-frozen hands (6 female; average age, 86 y; range, 84–89 y) were reconstructed using the House procedure (Fig. 1). Briefly, flexor digitorum superficialis (FDS) tendons were harvested and were split longitudinally into 2 equal-sized slips. Incisions were made dorsally over the extensor apparatus of each digit. One slip of the tendon was sutured and transferred 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

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and muscle. For Zancolli-lasso reconstructed hands, each FDS tendon was fixed via its suture proximally to simulate the origin of this muscle at the elbow. This provided preflexion of MCP joint to 40°/C14, simulating the average postoperative positioning in these patients due to the passive tension along the FDS muscle and tendon. Upon activation of the FDP and further flexion of the MCP joints, these FDS sutures went slack, providing no additional active load. For comparison, we also characterized the Zancolli-lasso hands with MCP joint preflexion of 0°, 20°, 60°, and 80°. Finger movement was video-captured from the radial side of the hand and digitized in Matlab (MathWorks, Inc., Torrance, CA). To define the relative order of joint flexion, the excursion of maximal angular change was determined for each joint, and these were compared for the different joints and for the different procedures. In addition, the maximal vertical distance from the fingertip to the palm (in the sagittal plane) was measured for each finger in each hand during flexion. These distances were normalized to the size of the hands based on x-ray measurements (Faxitron Specimen Radiography System, Tucson, AZ). All results were expressed as mean ± standard error of the mean (SEM).

**Statistical analysis**

The 2 primary endpoints were joint kinematics and fingertip-to-palm distance. These were compared between reconstruction procedures by analysis of variance with repeated measures. Statistical significance (α) was set at 0.05. Two-way analysis of variance compared maximal fingertip-to-palm distance of each procedure and explored interaction with finger (index, middle, ring, and little). Two-way analysis of variance was also used to compare angular changes at MCP, proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints as a function of procedure. In cases in which results were not significant, post hoc power analysis was performed.

**RESULTS**

**Kinematics**

At rest, before FDP activation with the motor, the House tenodesis produced 6° ± 9°, -1° ± 1°, and 10 deg; ± 3° of flexion at the MCP, PIP, and
DIP joints, respectively (mean across all hands and fingers ± SEM). The Zancolli-lasso produced 40° ± 6°, 2° ± 7°, and 6° ± 3° of resting flexion at the MCP, PIP, and DIP joints, respectively, with the elevated resting flexion at the MCP joint resulting from our proximal fixation of the FDS.

Kinematics were characterized by the order of angular change of the MCP, PIP, and DIP joints (Fig. 3). These differed between the 2 reconstructive procedures (P < .001). With the House procedure, maximal angular change occurred first in the MCP joint (at 19 ± 2 mm of FDP excursion) and then in the PIP joint (26 ± 1 mm) and DIP joint (31 ± 3 mm). Conversely, with the Zancolli-lasso procedure, maximal angular change occurred first in the PIP joint (14 ± 2 mm) and the DIP joint (14 ± 2 mm) and then in the MCP joint (21 ± 1 mm) joint.

For comparison, in the intrinsic-unloaded control hands, maximal change occurred first at the PIP joints (10 ± 2 mm of FDP excursion) and the DIP joints (27 ± 7 mm) and then at the MCP joints (31 ± 4 mm). For intrinsic-loaded (500 g) control hands, maximal change occurred first at the MCP joints (19 ± 2 mm), and then at the PIP joints (35 ± 3 mm) and the DIP joints (45 ± 1 mm). Thus, the MCP joint—first flexion of House more closely approximated the active-/loaded-intrinsic condition of the control hands compared with the IP joint—first flexion of Zancolli-lasso (Fig. 4).

Maximal fingertip-to-palm distance

Maximal fingertip-to-palm distances are displayed in Table 1. No significant difference was found in maximal fingertip-to-palm distance between the Zancolli-lasso and the House procedures. Each procedure produced significant or near-significant improvement compared with the unreconstructed control hands. As such, reconstruction in both cases represented an improvement over the intrinsic-inactivated scenario. Post hoc analysis revealed a power of 0.8 to show any difference in maximal fingertip-to-palm distance greater than 5 mm between the 2 procedures, and a power of 0.99 for any difference greater than 10 mm. For comparison, the
Intrinsic reconstruction is paramount for optimal grasp in reconstructive hand surgery for the tetraplegic patient. The purpose of this study was to compare 2 commonly used intrinsic balancing procedures with respect to creating functional grasp. We evaluated functional grasp based on 2 specific criteria of restoring normal order of joint flexion during grasp, beginning with the MCP joint and proceeding to the PIP and the DIP joints and creating maximum fingertip-to-palm proximity.

The 2 reconstructive procedures differed significantly with respect to their ability to restore the normal order of joint flexion. Specifically, the Zancolli-lasso reconstructed hands flexed IP joints first and then the MCP joints, resembling an unreconstructed, intrinsic-minus hand. Conversely, the House reconstructed hands flexed MCP joints first and then the IP joints, resembling an intrinsic-plus hand. Thus, kinematically, the House reconstructed hands better approximated normal intrinsic function. In these hands, activation of the FDP resulted in IP joint flexion, which tensioned the extensor apparatus. This tensioning of the House tenodesis across the MCP joint resulted in earlier flexion.

With respect to our second criterion, fingertip-to-palm distance, both reconstructive procedures showed improvements compared with control, whereas no difference was seen between the 2 procedures (Table 1). Because the Zancolli-lasso procedure could not mimic intrinsic-activated finger kinematics, the improvement in fingertip-to-palm distance over the unreconstructed hand was mainly caused by the initial MCP joint flexion of 40° that resulted from the reconstruction. So, whereas grasp in the House hand was more physiological, both reconstructive procedures optimized hand closure when evaluated based on maximal fingertip-to-palm closure. This measure provides a surrogate for how successfully hands will grasp objects. Further studies are needed to determine the validity of this surrogate and to compare the effects of these procedures on finger extension and hand opening.

Both the Zancolli-lasso and the House procedures are designed to promote MCP joint flexion and optimize grasp. The Zancolli-lasso procedure accomplishes this by affixing the FDS to itself around the A1 pulley. Because the FDS is paralyzed in most tetraplegic patients, this procedure relies on passive FDS tension to hold the hand in a position of fixed MCP joint flexion at rest. The House procedure also provides a tenodesis palmar to the MCP joint; but by inserting into the extensor apparatus, it also provides an extension force with respect to the IP joints. Thus, it effectively couples MCP joint flexion with IP joint extension, mimicking intrinsic function. Additional fundamental differences between the 2 procedures exist. Palmar incisions and dissection in the Zancolli-lasso hands are much more extensive than in the House hands. Further, the tenodesis in the Zancolli-lasso procedure results in a fixed resting flexion of the MCP joint.

Although no difference has previously been shown between the 2 procedures in terms of grip strength or activities of daily living, these technical differences have functional implications. For example, because MCP joint flexion is mechanically linked to PIP joint extension in the House procedure, this creates a more open hand during grasp, which we would expect to allow opening around larger objects, such as gripping the drive ring of the manual wheelchair. This effect is seen in Fig. 3, where, for the House
procedure, flexion proceeds in the order MCP joint, PIP joint, and DIP joint, whereas for the Zancolli-lasso, flexion proceeds in the order DIP joint, PIP joint, and MCP joint (see diamonds in Fig. 3). Further studies are warranted to compare finger extension and hand opening in these 2 procedures.

Several limitations exist for this experiment. First, finger flexion was measured with the hands in a palm-up position. This ensured that the fingers began in a fully extended position. However, this also meant that gravity may have assisted in IP joint extension until MCP joint flexion reached 90°. Whereas the House procedure inherently provides some IP joint extension regardless of gravity, the Zancolli-lasso does not. Therefore, this experimental condition may have benefitted the lasso hands in terms of artificially delaying IP joint flexion and optimizing tip-to-palm distance due to gravity. In addition, we chose a starting MCP joint flexion angle of 40° with the Zancolli-lasso reconstructions. In our clinical experience, this best estimates the average postoperative scenario. However, we also tested our Zancolli-lasso hands at starting MCP joint flexion angles of 0°, 20°, 60°, and 80°.

Kinematics (IP joint—first flexion) were identical in all scenarios (Fig. E1 [available on the Journal’s Web site at www.jhandsurg.org]), whereas maximal fingertip-to-palm closure increased with increasing degrees of MCP joint preflexion, as expected (Appendix A, available on the Journal’s Web site at www.jhandsurg.org). Finally, because all hands were amputated at the level of the radiocarpal joint, we were unable to assess the effect of wrist position on tenodesis efficacy.

Reconstructive hand surgery is an important tool in the physician’s skill set to optimize function and quality of life for the tetraplegic patient. Our findings suggest that both the Zancolli-lasso and the House procedures provide patients with a functionally larger grasp pattern than observed in hands with FDP transfers alone. However, only the House procedure restores hand kinematics resembling those of an intrinsic-activated hand.

### REFERENCES

**FIGURE E1:** Joint angles of the MCP, PIP, and DIP joints as a function of FDP excursion during grasp for the Zancolli-lasso reconstructed hands with varying degrees of MCP joint preflexion. Note that IP joint flexion precedes MCP joint flexion (see diamonds) for all conditions. Means (--) and standard errors (---) are shown over all hands (n = 6) and all fingers (index, middle, ring, and little). ◊ = excursion of FDP tendon where the greatest change of joint movement occurred for each joint.

**APPENDIX A. Zancolli-Lasso Maximal Fingertip-to-Palm Distances by MCP Joint Preflexion**

<table>
<thead>
<tr>
<th>MCP Preflexion</th>
<th>Finger</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Index</td>
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<tr>
<td>0°</td>
<td>65 ± 6</td>
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<tr>
<td>20°</td>
<td>67 ± 6</td>
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<tr>
<td>60°</td>
<td>76 ± 5</td>
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<tr>
<td>80°</td>
<td>80 ± 5</td>
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</table>

*Fingertip-to-palm distance of Zancolli-lasso hands at each finger with varying degrees of preflexion at the MCP joint. Distances are expressed as mean over all hands ± standard error of the mean in millimeters.*