Purpose  Regaining hand function has been identified as the highest priority for persons with tetraplegia. In many patients, finger flexion can be restored with a tendon transfer of extensor carpi radialis longus to flexor digitorum profundus (FDP). In the absence of intrinsic function, this results in a roll-up finger movement, which tends to push large objects out of grasp. To enable patients to grasp objects of varying sizes, a functional grasp is required that has a larger excursion of fingertip-to-palm distance than can be supplied without intrinsic function. The aim of this study was to quantify the role of intrinsic muscle force in creating a functional grasp.

Methods  Finger kinematics during grasp were measured on 5 cadaveric hands. To simulate finger flexion, the FDP was activated by a motor and intrinsic muscles were loaded at various levels (0, 125, 250, 375, or 500 g). Finger movement was characterized by the order of metacarpophalangeal, proximal interphalangeal, and distal interphalangeal joint flexion and by the maximal fingertip-to-palm distance during finger closure.

Results  Without any intrinsic muscle contribution (0-g load), FDP activation resulted in flexion of all 3 joints, whereby flexion began at the proximal interphalangeal joint, followed by the distal interphalangeal joint, and then the metacarpophalangeal joint. With increasing intrinsic muscle load, finger flexion was initiated at the metacarpophalangeal joint, followed by the proximal interphalangeal and distal interphalangeal joints. This altered joint flexion order resulted in a larger maximal fingertip-to-palm distance during finger flexion. The difference between the 2 extreme conditions (0 g vs 500 g of intrinsic muscle load) was 19 mm.

Conclusions  These findings demonstrate that simultaneous activation of the FDP and the intrinsic muscles results in an apparently more functional hand closing compared with FDP activation alone because of altered kinematics and larger fingertip-to-palm distances.

Clinical relevance  These findings suggest that intrinsic muscle balancing during reconstruction of grasp in tetraplegic patients may improve function. (J Hand Surg 2013;38A:2093–2099. Copyright © 2013 by the American Society for Surgery of the Hand. All rights reserved.)

Key words  Grasp, hand, intrinsic muscles, tendon transfer, tetraplegia.
Regaining arm and hand function has been identified as the highest priority for persons with tetraplegia.\textsuperscript{1,2} Recovering even partial function can have an enormous impact on independence, which enhances quality of life.\textsuperscript{3} Restoration of finger flexion is an achievable goal in reconstructive surgery of many tetraplegic hands. It can be performed if both the extensor carpi radialis longus and brevis are fully innervated, in which case the extensor carpi radialis longus is transferred to the flexor digitorum profundus (FDP),\textsuperscript{4} which enables patients to grasp and hold objects. However, by restoring FDP function only, finger tips coming into full flexion approach the bases of the fingers rather than the center of the palm.\textsuperscript{5} This happens because finger flexion begins at the distal interphalangeal (DIP) joint, and fingers curl into flexion rather than following a large arc, which would provide a broad sweeping movement.\textsuperscript{6} The roll-up finger flexion tends to push large objects out of grasp\textsuperscript{5} and is, therefore, considered less functional in daily life.

In normal hand function, the intrinsic muscles, both the lumbricals and the interosseus muscles, balance finger movement\textsuperscript{7} and create this broad sweeping movement. Besides abducting and adducting the fingers, they are responsible for coupling metacarpophalangeal joint (MCP) flexion with interphalangeal (IP) joints extension.\textsuperscript{8,9} For 2-dimensional finger movement during grasp, the lumbricals and the interossei provide the same function, as shown by Leijnse et al.\textsuperscript{10} Because their function is redundant in the sagittal plane, we refer to them as 1 entity, the intrinsics. Intrinsic function is so important that even when patients have neither functional intrinsic muscle nor a sufficient number of transferable muscles to reconstruct them with an active tendon transfer, passive tenodeses are used to substitute for intrinsic muscle function.\textsuperscript{11,12}

We characterize functional hand movement for tetraplegic persons as a large fingertip-to-palm distance during flexion because this enables them to grasp objects of varying sizes and shapes necessary for activities of daily life. The exact contribution of the intrinsic muscles to this function is incompletely understood. Therefore, the purpose of this study was to quantify the role of intrinsic muscle force in creating a functional grasp. We hypothesized that increasing intrinsic muscle contribution would result in a more functional grasp.

**MATERIALS AND METHODS**

**Sample preparation**

Five fresh-frozen hands were used for the experiment (3 male, 2 female; average age, 75 y; range, 59–88 y). Hands had been amputated at the level of the radiocarpal joint. For each hand, dissection and data collection were performed on the same day. During preparation and testing, hands were maintained at room temperature, and tendons were kept moist with Ringer solution.

The thumb was amputated at the MCP joint to permit clear video recording. The volar skin was excised distally to the level of the middle phalanx, and the palmar aponeurosis was resected. The FDP tendons were identified at the level of the carpal tunnel and the ends individually sutured proximally with 2-0 suture. The palmar carpal ligament remained intact. Each lumbrical was identified by its origin on the FDP and insertion into the radial lateral band. For our purposes, intrinsic muscle insertion was defined as the tendinous insertion of the lumbricals into the radial lateral bands and were tagged with 2-0 suture. The lumbrical and interossei origins were left intact. All volar tendons and affixed sutures were then passed proximally through the carpal tunnel. Dorsal skin was excised entirely. Tendons of the extensor digitorum communis (EDC) were sutured individually with 2-0 suture at the level of the wrist. Owing to the scarce contribution of EDC to the extensor apparatus of the little finger in most hands, the extensor digiti quinti tendon was sutured for this digit.

Kirschner wires (1.1 mm) were drilled into each metacarpal and phalanx dorsally to mark motion. The angle between the wire and its respective bone was measured for later analysis. To facilitate data collection (ie, prevent markers from obscuring one another), each intrinsic muscle loading condition was performed once with wires in the index and ring fingers and once with wires in the middle and little fingers. The order was randomized. Two Schanz pins were drilled into the base of the third metacarpal dorsally to affix and stabilize the hand during experimentation.

**Mechanical testing**

The hand was positioned palm up with fingers fully extended (Fig. 1). The FDP sutures were attached to a single dual-mode servo-motor (Aurora Scientific, Model 310, Aurora Inc., Ontario, Canada). To approximate passive resistance, we affixed EDC sutures to a 50-g mass, which was allowed to move via a pulley and created a fixed resistance. Intrinsic muscle sutures were affixed via a pulley to 0, 125, 250, 375, and 500 g masses, which were also allowed to move. The order in which these intrinsic loads were trialed in each hand was randomized. Five hundred grams represented the maximal weight that
could be attached to the radial lateral bands so that all hands were starting with an extended MCP joint and approximates the maximum tetanic tension of the intrinsic muscle.13

For each experimental condition, the motor pulled the FDP tendon 50 mm in a linear deformation pattern and at a velocity of 5 mm/s. This excursion was determined to be sufficient to create a closed fist. A video camera was positioned on the radial side of the hand perpendicular to the plane of movement and at a fixed distance to record marker movement during FDP excursion.

Following all trials, each hand was x-rayed (Faxitron Specimen Radiography System, Tucson, AZ) to determine bone lengths. Films were digitized (Bio-Rad GS-800 calibrated densitometer, Hercules, CA) and loaded into Adobe Photoshop CS6 (Adobe, Inc., San Jose, CA). Metacarpals and phalanges were measured for each hand and calibrated by a 100-mm marker included in each x-ray image (Table 1).

### Kinematic analysis

The 2-dimensional position of the markers attached to each finger was digitized in Matlab (The MathWorks Inc., Natick, MA) at a frame rate of 1 Hz. The vectors of the bones and the resulting joint angles of the MCP, proximal interphalangeal (PIP), and DIP joints were calculated from the marker vectors and their relative angles to the bones. To define the relative order of joint flexion, the time point of maximal angular change was determined for each joint, and these were compared for the different joints and for the different experimental conditions. Other methods of assessing these kinematics, such as joint angle at 50% excursion and time to reach 50% total angular change, were trialed, and results mirrored those presented here.

To calculate the 2-dimensional position of each joint, the magnitude of the bone vectors was scaled to the measured bone length. The vertical distance from the fingertip to the palm (sagittal plane) was calculated for each finger in each hand.

### Statistical analysis

Two-way repeated measures analysis of variance was performed to evaluate the effect of the intrinsic muscle load on grasp capacity (maximal fingertip-to-palm distance). Within-subject factors were intrinsic muscle load (0, 125, 250, 375, or 500 g) and finger (index, middle, ring, or little finger). To analyze the effect of intrinsic muscle load on finger kinematics (order of joint flexion as defined previously), a 3-way repeated measures analysis of variance was performed. The within-subject factors were intrinsic muscle load, finger, and joint (MCP, PIP, or DIP joint). Level of significance (α) was set to P < .05. Bonferroni post hoc tests adjusted for multiple comparisons were conducted to identify intrinsic muscle loading conditions significantly different from one another.

### RESULTS

Increasing intrinsic muscle load resulted in a qualitatively different finger movement compared with no intrinsic muscle load (Fig. 2 and Video 1 [available on the Journal’s Web site at www.jhandsurg.org]).
With no intrinsic muscle load, fingers moved in a roll-up motion with the PIP and DIP joints flexing early. With increasing load, the IP joints flexed later relative to the MCP and fingers moved without early digital roll-up.

Loading intrinsic muscles altered the closing cascade of the fingers (Fig. 3), especially the order of flexion of MCP and PIP joints. With no intrinsic muscle load, the PIP joint flexed first, followed by the DIP and MCP joints (Fig. 3, colored diamonds). The same movement pattern was found for an intrinsic muscle load of 125 g, except that the MCP joint flexed before the DIP joint. With an intrinsic muscle load of 250 g, the MCP and PIP joints flexed similarly, and the maximal angular change occurred approximately at the same time (Fig. 3, diamonds). With a load of 375 g and above on the intrinsic muscle, the MCP joint flexed first, followed by the PIP joint. Under these conditions, the DIP joint flexed after the other joints. Statistical analysis revealed that there was a significant difference in the order of joint movement (quantified by the excursion at which
maximal angular change occurred) between intrinsic muscle load conditions ($P = .005$) and a significant interaction between intrinsic muscle load and joint ($P < .001$). There was no difference in the order of joint movement between fingers ($P = .190$), and there was no finger $\times$ joint ($P = .358$) or intrinsic muscle load $\times$ finger $\times$ joint ($P = .882$) interaction. Bonferroni post hoc tests did not reveal significant differences between individual comparisons for interaction between intrinsic muscle load and joint, the outcome of most clinical relevance. This indicates that, even though there is a main effect of load, sample sizes may have been too small to demonstrate specific paired differences.

Increasing intrinsic muscle load altered the maximal fingertip-to-palm distance during finger flexion. Lower load conditions resulted in a roll-up finger flexion whereby the fingertips followed a lower arc over the palm, whereas increasing load allowed fingertips to follow a higher arc (Fig. 4A). This resulted in a significant difference in the maximal distance between fingertip and palm between the conditions ($P < .001$; Table 2). For example, the mean maximal distance of the middle finger increased from 64 mm (0 g) to 82 mm (500 g). Bonferroni post hoc tests revealed significant differences only between the 0-g and the 125-g conditions ($P = .036$) owing to the lower standard errors of the mean (SEMs) at these conditions, although many other pairs trended toward significance. The difference in fingertip arc was related to the order of joint flexion, which is seen by plotting MCP joint versus PIP joint angle (Fig. 4B). As intrinsic muscle load increased, MCP joint angle changed first, resulting in a more horizontal initial excursion of the trace.

### Table 2. Maximal Distance Between Fingertip and Palm

<table>
<thead>
<tr>
<th>Load (g)</th>
<th>Finger</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Index</td>
<td>Middle</td>
</tr>
<tr>
<td>0</td>
<td>54 $\pm$ 3</td>
<td>64 $\pm$ 4</td>
</tr>
<tr>
<td>125</td>
<td>60 $\pm$ 2</td>
<td>68 $\pm$ 4</td>
</tr>
<tr>
<td>250</td>
<td>66 $\pm$ 2</td>
<td>75 $\pm$ 3</td>
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<tr>
<td>375</td>
<td>70 $\pm$ 3</td>
<td>80 $\pm$ 3</td>
</tr>
<tr>
<td>500</td>
<td>72 $\pm$ 3</td>
<td>82 $\pm$ 2</td>
</tr>
</tbody>
</table>

Maximal distance between fingertip and palm (mean over all hands $\pm$ standard error the mean in millimeters) and results of the statistical analysis. Post hoc test load indicates the intrinsic muscles load conditions where significant differences were found. $P$ refers to the 3 values obtained from 2-way analysis of variance of the data using load and finger as grouping factors.

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**FIGURE 4:** A Path of the tip of the middle finger during flexion relative to the plane of the palm for all intrinsic muscle load conditions. Mean calculated across hands ($n = 5$). Note larger arcs with increasing intrinsic muscle load. B MCP joint angle plotted against PIP joint angle for intrinsic muscle load conditions to illustrate the interaction between these joint motions as a function of intrinsic muscle load. Means were calculated over all hands ($n = 5$) and all fingers (index, middle, ring, and little). Note the more horizontal initial excursion with increasing intrinsic muscle load owing to larger initial MCP flexion.
DISCUSSION

This study demonstrated the kinematic influence and potential for functional advantage of providing intrinsic muscle function after paralysis. Increasing intrinsic muscle contribution increased the distance between fingertip and palm during finger flexion, resulting in a theoretically more functional grasp (Fig. 4A). The difference between the 2 extreme conditions for the middle finger (0 g vs 500 g of intrinsic muscle load) was 19 mm, which represents a large difference in finger movement when considering activities of daily life. This can determine whether objects can be grasped and lifted independently or whether assistance will be required. For example, grasping a standard beverage can, which has a diameter of 66 mm, may theoretically not be possible if a person does not have active intrinsic muscle function. This study showed that, if grasp is powered by the FDP alone, the middle finger will not be able to grasp the can and will simply push the can away. The results showed that grasping the can with the middle finger is theoretically only possible if the intrinsic muscles are loaded with at least 250 g. Of course, actual grasp results from an interplay of all 4 fingers, and as a result of the different size of each finger, there was a significant difference in fingertip-to-palm distance among fingers (index, middle, ring, or little finger). Further study is required to determine whether this theoretical advantage bears true, and, if so, whether it is clinically relevant.

The difference in fingertip-to-palm distance with increasing intrinsic muscle load described previously resulted from the altered kinematics of joint flexion. In the absence of intrinsic muscle loading, FDP activation resulted in flexion beginning at the PIP joint, followed by the DIP joint and then the MCP joint (Fig. 3, diamonds represent maximum angular change for each joint). These results support the findings of Kamper et al., who analyzed whether it is biomechanically feasible for extrinsic flexors to initiate concurrent flexion at all 3 finger joints. Their results demonstrated that shortening of the extrinsic flexors resulted in simultaneous flexion of all 3 joints. The rates of change of the DIP and PIP joint angles were greater than that of the MCP joint.

Even though the intrinsic muscles are not necessary to produce finger flexion, they are important to mediate finger flexion. With greater intrinsic muscle loads, MCP joint flexion starts earlier, followed by IP joint flexion. This can be explained in part by the contribution of the intrinsic muscle to the MCP joint flexion moment. Recent studies showed that the intrinsic muscles produce a considerable fraction of the MCP flexion moment. Depending on the finger, the following contributions of the intrinsic muscle to MCP flexion moment have been found: index, 12% to 26%; middle, 5% to 8%; ring, 2% to 13%; and little, 15% to 28%.

Intrinsic muscle activation contributes not only to earlier MCP joint flexion but also to the delay in IP joint flexion. While analyzing the contribution of the intrinsic and extrinsic muscles to the extension of the DIP joint, Murai et al. found an almost equal contribution of these muscles. At the highest intrinsic muscle load condition of the present study, the IP joints flexed with a delay (Figs. 3 and 4B). Whereas the MCP joint was already fully flexed and at its terminal position, the IP joints were still flexing. Thus, the intrinsic muscle-mediated coupling of MCP joint flexion to IP joint extension modulated the FDP-mediated IP joint flexion. This resulted in the largest observed fingertip-to-palm distance (Fig. 4A). A similar idea was presented by Landsmeer et al. who studied the mechanisms of finger control based on electromyographic measurements. Starting with all joints extended, subjects were asked to flex the IP joints first and subsequently the MCP joint. This movement resulted in a measurable electrical signal from the FDP and EDC, but not the intrinsic muscles. Conversely, when moving from the same starting position but flexing the MCP joint alone without IP joint flexion, only the EDC and intrinsic muscles were activated while the FDP remained silent.

In normal, everyday finger movement, hand muscles work together and either sequentially or simultaneously activate, depending on the task. In this study, these task-dependent motor control patterns were not addressed because the muscles were either active or not during the entire excursion. Although this may not represent intact hand function, it does reflect the situation of tetraplegic patients after surgical reconstruction of finger flexion. Depending on the lesion level, finger flexion can be restored by tendon transfer; however, most patients do not have a sufficient number of transferable muscles to also reconstruct the intrinsic muscles by a tendon transfer. In these patients, passive intrinsic muscle balancing is accomplished by tenodesis. Two such procedures, the Zancolli-lasso and House reconstructions, are compared in part 2 of this study (Intrinsic hand muscle function II: kinematic comparison of two reconstructive procedures. Manuscript submitted for publication). In the future, nerve transfers may also play a larger role in direct reactivation of the intrinsic muscles.
Limitations of this study include the small sample size and the age of the tested hands. Although degenerative muscle changes may have been present in our study (age range, 59–88 y), finger movement was generated by the external forces of the motor and weights; thus, muscular changes were not relevant. Another limitation was the fact that the kinematic analysis was performed in 2 dimensions. The majority of finger movement during grasp occurred in this sagittal plane; however, there was some out-of-plane motion as well. Specifically, the little finger curled toward the middle of the palm during grasp, which was not considered. Because neither the kinematic nor the fingertip-to-palm results were dependent on the little finger, we concluded that 2-dimensional analysis adequately captured the grasping motion. The choice of 50 g of fixed resistance applied to EDC was necessarily arbitrary. The exact magnitude of this force is unknown and could vary throughout finger flexion. However, we do not believe that this would have biased our results. Finally, this study used constant intrinsic muscle loads and, therefore, cannot provide information regarding appropriate timing of intrinsic muscle activation.

Our results illustrate the importance of intrinsic muscle balancing during reconstruction of grasp in tetraplegic patients. The theoretical improvement of grasp with increasing fingertip-to-palm distances should be verified experimentally, and the kinematic outcome of different reconstruction techniques should be compared with respect to functional grasp.

REFERENCES