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Influence of Index Finger Proximal Interphalangeal Joint Arthrodesis on Precision Pinch Kinematics

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Abstract

Purpose—To evaluate the impact of proximal interphalangeal (PIP) joint arthrodesis on the kinematics of precision pinch.

Methods—Eleven healthy subjects performed index finger-thumb pinch motions under 4 conditions: unrestricted thumb and index finger (CONTROL), fusions of the PIP joint of the index finger in flexion of 30° (PIP30), 40° (PIP40), and 50° (PIP50). Fusion was simulated with metallic splints. Kinematics of the thumb and index finger were recorded with a motion capture system.

Results—Proximal interphalangeal joint fusion at 30°, 40°, and 50° restricted maximal pinch span between the thumb tip and index finger tip by 6, 10 and 14 % respectively. At the time of pulp contact, PIP fusion led to an increase in index metacarpophalangeal joint flexion angle for the PIP30 condition and an increase in variability of thumb tip location for the PIP50 condition. Furthermore, the dynamic coordination between joint angles throughout the movement was affected by PIP fusion.

Conclusions—This study reports impairment in the kinematics of precision pinch associated with index finger PIP joint fusion. A PIP joint fusion at 40–50° leads to a more natural precision pinch posture but restricts aperture as well as a reduces pinch precision.

Type of study/level of evidence—Prognostic, Level I.

Keywords

Proximal Interphalangeal Joint; Arthrodesis; Precision Pinch; Finger Coordination

Introduction

Arthrodesis of finger interphalangeal joints is common treatment for inflammatory arthritis such as scleroderma [1], gout [2], and osteoarthritis [3]). Despite continuous improvements in implant design, proximal interphalangeal joint (PIP) arthroplasty of the index finger has

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been associated with mixed results regarding rate of implant revision and restoration of mobility [4,5,6,7]. Arthrodesis remains the often preferred treatment for posttraumatic arthritis of the index PIP joint [8]. When arthrodesis leads to successful fusion, it provides a painless stable joint but obviously fails to recover the biomechanics of a normal finger. To investigate the effect of PIP joint fusion on hand performance, Woodworth et al. [9] analyzed the time to complete daily life activities and the range of motion of the metacarpophalangeal (MCP) joint required to achieve them. They reported that only a few precision pinch tasks were associated with an increased MCP joint range of motion and concluded that, overall, PIP joints fixed at 40° of flexion did not affect MCP joint motion. Woodworth et al. [9] observed compensatory movements of the index finger distal interphalangeal (DIP) joint and the thumb joints but did not record them.

A functional hand task such as precision pinch relies on an efficient coupling that originates both from anatomical (e.g. multi-joint muscles) and neurophysiological constraints [10,11]. This coupling results in specific inter-joint coordination [12,13] that the analysis of a single joint range of motion cannot explain. To better understand the impairment associated with fusion of an individual joint, the whole kinematic chain involved in the movement needs to be examined. The aim of this study was to investigate the effect of arthrodesis of the index finger PIP joint on precision pinch kinematics. We hypothesized that PIP joint fusion would lead to 1) decreased maximal pinch aperture, 2) increased variability of joint angles and digit tip locations at the time of pulp contact during repeated precision pinches, and 3) decreased joint coordination throughout the pinch movement. Furthermore, the recommended posture for fusion varies depending on factors such as pinch force requirement and esthetic concerns [14]. As a subsidiary analysis, we consequently tested 3 different angles of fusion.

Methods

Participants

Eleven healthy right handed volunteers (mean $\pm$ SD, age: 24 ± 4 years; body mass: 79 ± 9 kg; height: 177 ± 6 cm; hand length from the proximal wrist crease to the tip of the middle finger: 22.2 ± 1.2 cm) participated in the study. All participants had no previous history of neuropathies or trauma to the upper extremities and signed an informed consent form approved by the local institutional review board.

Experimental Setup

Each participant sat on a height-adjustable chair in front of the testing table with the right shoulder in approximately 50° of flexion and 0° of abduction. The arm was placed in a custom-made arm holder [15] that stabilized the elbow at approximately 90° of flexion, the forearm in supination, and the wrist in 20° of extension. Participants were asked to perform a cyclic pinching motion with the thumb and index finger, opening as widely as possible and closing to make pulp contact as accurately as possible. The pace was standardized at a frequency of 1 cycle per second with an audio metronome in order to eliminate the influence of speed [16]. During the pinching task, the subjects kept their eyes closed to eliminate visual feedback.

Repetitive pinching tasks were tested in 4 conditions: unrestricted thumb and index finger (CONTROL), fusions of the PIP joint of the index finger at a flexed position of 30° (PIP30), 40° (PIP40), and 50° (PIP50). The experimentally simulated fusion was achieved by aluminum splints secured to the dorsal and volar aspects at the level of the index finger's proximal and middle phalanges with circumferential adhesive tape [9] (Figure 1). Special care was taken with splint placement to avoid hindering motion at the MCP and DIP joints. A hole was made into the dorsal aluminum splint so that the reflective marker on the PIP

joint remained at the same location throughout the different conditions, which maximized the consistency of angle calculations. Participants performed 3 trials (30 sec each) in each of the 4 conditions. Prior to the recording session, each subject performed a single practice trial (unrestricted, 30 sec) to become familiar with the task.

Data Collection

Pinch motion data were collected with a 6-camera motion capture system (Vicon MX, Oxford, UK) at a sample frequency of 100 Hz and filtered using a fourth-order Butterworth low-pass filter with 20 Hz cut-off frequency. Spherical reflective markers (4 mm in diameter) were attached to the dorsal aspects of the thumb, index finger, and hand with double-sided tape (Figure 1). Markers were located on the thumb nail, the thumb interphalangeal (IP) joint, the thumb metacarpophalangeal joint (MCP₁), and the trapeziometacarpal joint (TMC). Additional markers were placed on the index finger nail, the distal interphalangeal joint (DIP), the proximal interphalangeal (PIP) joint, and the metacarpophalangeal joint (MCP₂). Markers were also placed on plastic casts secured to the dorsum of proximal phalanges of both digits as well as on the thumb metacarpal. These markers defined the coronal planes of the segments. Given the unique degree of freedom (DoF) in flexion/extension of interphalangeal joints, the radio-ulnar direction for the distal and middle phalanges was assumed to be the same as for the proximal phalanx. Additional markers were placed on the hand dorsum to define the index and middle metacarpal coordinate systems. The second metacarpal reference system was used to calculate MCP₂ joint angle and the third metacarpal was used to compute the trapezium's reference system according to Cooney et al. [17] who reported that the trapezium is rotated by 46° of flexion, 35° of abduction and 82° of supination with respect to the third metacarpal. The TMC joint angle was then computed from the reference systems of the thumb metacarpal with respect to the trapezium.

The motion of 6 joints was recorded: the thumb IP, MCP, and TMC joints and the index finger's DIP, PIP, and MCP joints. Joint angles were calculated following Euler angles' sequence *flexion* (+), *external rotation* (+), and *abduction* (+).

Data Analysis

The first 5 cycles of each trial were excluded from data analysis. Maximal aperture was calculated as the maximum distance between thumb and index finger tip markers during each trial. The opening and closing phases were identified and the subsequent analyses focused on the closing (pinching) phase only. Onsets (start of pinch) and completions (pulp contact) of the closing phase were identified at the instants when aperture velocity rose above or fell below 5% of the peak velocity, respectively [12]. Pearson's coefficients of correlation between joint angles were calculated during the closing phase of each pinch cycle. At the time of pulp contact, joint angles (mean±SD) and digit tip marker locations were analyzed. To estimate cycle-to-cycle variability (within a trial) of tip marker location, the dispersion (D) was calculated as the mean distance between tip location and the mean tip location (Eq 1),

$$D = \frac{1}{n} \sum_{i=1}^n \left(\sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2 + (z_i - \bar{z})^2} \right) \quad (\text{Eq 1})$$

where n (=25) is the number of cycles per trial, and $(\bar{x}, \bar{y}, \bar{z})$, are the mean coordinates of marker location at the time of pulp contact. To account for the movement of the whole hand,

marker coordinates were transformed to the second metacarpal coordinate system before the calculation of dispersion.

Results of each condition were represented as the average across the 3 trials. Statistical significance of the effects of fusion condition was evaluated with repeated measures one-way analyses of variance (ANOVA). If assumptions of normality and equal variance were not met, then ANOVA on ranks was used. A significance level of 0.05 was used.

Results

Maximum Pinch Aperture

Maximal aperture was significantly restricted with increasing PIP fusion angle by 6, 10, and 14 % for PIP30, PIP40 and PIP50 conditions, respectively ($p < .001$). See Figure 2

Joint Angles at the Time of Pulp Contact

Changes in abduction-adduction joint angles throughout the pinch movement were small and not affected by PIP fusion ($p = .21$). Therefore the following analysis addresses the flexion-extension angles only. At the time of pulp contact, the unrestricted MCP and DIP joint positions of the index finger were affected by PIP fusion. DIP joint angle was $11 \pm 9^\circ$, $15 \pm 7^\circ$, $16 \pm 6^\circ$ and $18 \pm 8^\circ$ for the CONTROL, PIP30, PIP40, and PIP50 conditions, respectively. The DIP joint angle increased with increasing PIP fusion angle ($p < .001$). The MCP joint angle significantly increased in the PIP30 condition ($62 \pm 5^\circ$) in comparison to the CONTROL condition ($53 \pm 8^\circ$) ($p < .01$), but the MCP joint angle did not differ significantly among the CONTROL, PIP40, and PIP50 conditions. At the time of pulp contact, thumb joint positions did not change significantly ($p = .14$) with respect to the CONTROL. In addition, PIP joint fusion did not lead to a change in the variation (standard deviation) of individual joint angles at the time of pulp contact ($p = .21$).

Digit Tip Location Variability

The PIP joint fusion did not affect index tip variability ($p = .10$). However, there was a significant increase in thumb tip dispersion from the CONTROL condition (3 ± 1 mm) to the PIP50 condition (3 ± 1 mm) ($p < .01$). The dispersion in thumb tip location in a representative subject is illustrated in Fig. 3.

Dynamic Joint Coordination

Coefficients of correlation (R) were generally high ($> 0.84 \pm 0.15$) for all pairs of joints and all conditions except for IP-TMC and MCP₂-TMC, which were 0.51 ± 0.42 and 0.70 ± 0.36 , respectively. There was a significant ($p < 0.001$) decrease in joint coordination associated with PIP joint fusion on 2 pairs of angles: DIP-MCP₂ and DIP-IP (Figure 4). Details of coefficient of correlation for those pairs are reported in Table 1. There was no effect of PIP fusion on other pairs of angles.

Discussion

This study investigated the impairment of precision pinch associated with a simulated PIP joint fusion at 30° , 40° , and 50° of flexion. Our first aim was to analyze the restriction in pinch ability associated with PIP joint fusion. We quantified the maximal pinch aperture as an indicator of the ability to grasp large objects and, as anticipated, PIP joint fusion restricted maximal pinch aperture – the greater the fusion angle, the more restriction of pinch aperture.

Our second aim was to analyze the effect of PIP joint fusion on thumb and index finger kinematic coordination. In order to compensate for the loss of a degree of freedom, the other joints have to compensate. Results of joint angles at the time of pulp contact showed that the index finger (DIP and MCP₂ joints) was the only digit to compensate for the loss of its PIP joint motion. The natural PIP joint angle for pinching recorded during the CONTROL condition was around 44° which is close to the PIP40 and PIP50 conditions. This most likely explains why the MCP₂ joint angle at the time of pulp contact only changed in the PIP30 condition and not in the PIP40 and PIP50 conditions. A PIP joint fusion angle of 40°–50° approximates a natural index finger posture for the pinching thin objects such as a card. To account for the loss of PIP joint motion, any combination of the remaining 5 joints may potentially be used. There was no significant compensation in the thumb joint angles indicating that the index finger is preferably used to adapt the pinch posture. This result is similar to previous studies reporting that index finger posture is also the factor accounting for changes in the pinch span between the thumb tip and finger tip [18,19]. Thus, the results of this study support the thumb's primary role of providing a fixed support on which the index finger rests.

Cycle-to-cycle variability of joint angles and digit tip locations at the time of pulp contact was used as an indicator of pinch precision. Overall the cycle-to-cycle variability within a trial was small ($\leq 3^\circ$) and, contrary to our hypothesis, PIP joint fusion did not affect joint angle variability. We also investigated the cycle-to-cycle variability of digit tip locations at the time of pulp contact. Despite not finding significant changes in individual joint variability, our analysis demonstrated that overall variability of the end-effectors was affected by PIP joint fusion: thumb tip location was more variable in the PIP50 than in the other conditions. The increased variability in thumb tip location but not in joint angles may be due to the fact that changes in individual joints were not large enough to show significance. However, addition of the small variability of the 3 joints led to a significant overall increased variability of thumb tip location. Cole et al. [20] reported that, during unimpaired precision pinch, joint angles were naturally variable from one cycle to another but covaried so that the variability of contact point between digit tips was minimal. Thus, more than the underlying joint angles, consistency of the end-effectors' location relative to each other is the critical parameter to ensure a reliable pinch and to prevent dropping objects. The methodology employed here did not record the location of contact point between digits; but it is likely that if thumb tip location was more variable during PIP50, the contact point between the 2 digits was variable as well. In that sense, results suggest that a large (around 50°) fusion angle may potentially be detrimental for precision pinch. However, even if statistically significant, the small difference has to be put into perspective of measurement error. Clinical significance also needs further investigation to definitely state on the importance of a small increase in thumb tip variability on precision pinch.

Previous studies showed that natural finger motions exhibit strong inter-joint and inter-finger coordination [12,13], and finger coordination is vulnerable to pathological conditions [15,21,22]. In this study, we found that the dynamic coordination (i.e. throughout the movement) between joint angles was affected by PIP joint fusion: both intra-finger (DIP-MCP₂) and inter-finger (IP-DIP) joint coordination decreased as angle of PIP joint fusion increased. Coordination between the DIP and MCP joints of the index finger is most likely due to the action of the flexor digitorum profundus, a multiarticular muscle whose contraction concurrently flexes the MCP₂, PIP, and DIP joints. Restricting the motion of 1 of those joints alters that anatomical coupling mechanism and may explain the impairment of dynamic coordination. On the other hand, flexion of index finger DIP and thumb IP joints is achieved by different muscles: flexor digitorum profundus for the index finger and flexor pollicis longus for the thumb. However, the 2 muscles are not completely independent as anatomical interconnections [23] and coactivation [24] exist. Those 2 sources of coupling

provide an efficient control mechanism for the 2 digits, which often have to work together. A PIP joint fusion likely alters the proprioception in the index finger and may subsequently hinder the neural coupling between the 2 digits.

Limitations of this study include simulating a fusion of the PIP joint with splints. We monitored the method's effectiveness and found that the fused PIP joint was not completely rigid and exhibited small mobility (within 4°) at the time of pulp contact. This variation may have led to underestimating the impairment experienced by patients with surgically fused PIP joints. In addition, arthrodesis of the PIP joint results in some shortening of the finger that may change the contact position between the 2 digits. Furthermore, diseases that lead to joint fusion are commonly associated with adjacent impairment such as arthritis at other joints and impaired muscle function. These factors were not considered in this study.

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Figure 1.
A pinch posture with makers attached and the PIP joint splinted.

Figure 2.
Restriction in thumb-index finger aperture with respect to PIP fusion angle.

Figure 3. Representative 2D stick figures of the thumb and index finger at the time of pulp contact over multiple cycles (CONTROL and PIP50 Conditions). XY represents the sagittal plane of the index metacarpal.

Figure 4. Representative angle–angle plots of the thumb and index finger joints during pinch. The straight lines are derived from linear regression.

Table 1

Intra- and inter-digit coefficients of correlation

	Intra-digit	Inter-digit
	DIP-MCP ₂	IP-DIP
CONTROL	0.93±0.06	0.91±0.03
PIP30	0.89±0.07*	0.91±0.06
PIP40	0.87±0.07*	0.88±0.05
PIP50	0.86±0.06*	0.83±0.06*

* indicated a significant difference ($p<0.01$) with respect to CONTROL