Identification of three movement phases of the hand during lateral and pulp pinches using video motion capture

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Abstract

Background Hand injuries affect a person's ability to engage successfully in activities of daily living (ADLs). Video motion capture (VMC) facilitates measurement of dynamic movement. No study to date has used VMC as a means of quantifying the simultaneous movement patterns of all joints of all digits of the hand during active purposeful movement.

Method The purpose of this study was to analyze all joints of all five digits during active completion of the lateral and pulp pinches. VMC data were collected from four participants during completion of two pinches. Joint angles were plotted to facilitate identification of movement patterns.

Results Range of motion recorded in all joints with VMC, excluding flexion of the thumb carpometacarpal of both pinches, coincided with the normative goniometric data. Three phases were observed: initiation, preshaping, and pinch phases. Patterns of movement in all digits were identified for the two pinches.

Conclusion VMC is a feasible and valid method for objectively quantifying dynamic movement of multiple joints simultaneously. The results provide new insight to the dynamics of hand movement as well as a basis for subsequent evaluations of movement patterns performed in ADLs and instrumental ADLs.

Keywords Biomechanics · Finger · Video motion analysis

Background and Purpose

Dexterity and strength of the human hand are fundamental attributes that enable humans to manipulate and grasp objects [4, 33]. The manipulation and grasping of an object is also known as prehension [9]. The complexity of the combination of finger and thumb movements as well as the strength used is essential to the completion of many activities of daily living (ADLs) and instrumental activities of daily living (IADLs; those tasks central to independent community living beyond simple self-care) [24, 33, 37].

Injuries of the hand such as fractures, tendon lesions, and wounds are the most common form of injury and account for 20 % of emergency room visits [3, 39] and can affect a person's ability to accurately perform the prehension patterns that allow successful engagements in ADLs and IADLs. With the complexity and rate of injury to the hand, it is important to understand and define normal movement patterns. Currently, there is no quantitative dynamic description of the movement patterns of all the digits and joints while actively completing two pinches.

There is a growing interest in measures that reflect a client's performance of ADLs and IADLs [2, 4, 24, 38]. The assessments that are available can evaluate aspects of ADLs and IADLs but do not assess the completion of whole tasks. The Moberg pickup test, Jebsen–Taylor hand function

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test, Carroll test, and Sollerman hand function test are a few of the assessments that are currently used [39] to assess a wide array of hand deficits arising from carpal tunnel syndrome, stroke, tetraplegia, transplantation, neuropathies, and nerve injuries [1, 2, 5, 6, 17, 20, 31, 34, 41, 43, 45]. These assessments examine components of ADL and IADL tasks as well as the strength used to complete certain tasks, or the speed of performance, but fail to assess the quality of the movement over time [39]. Most importantly, the specific area contributing to or compensating for the movement deficit cannot be identified by the current measurements.

Currently, the goniometer is the most commonly used device for measuring joint angles [22]. When used in accordance with guidelines for starting position and placement, the goniometer has high intra-rater reliability and validity [11]. However, the goniometer is administered by a therapist and thus has an intrinsic component of subjectivity and is prone to inter-rater differences. In a study of 51 therapists, results indicated that intra-rater goniometric measures fell within 4–5° and inter-rater goniometric measures fell within 7–9° 95 % of the time [16]. More importantly, the goniometer cannot provide data about the dynamics of hand movement since it is limited to the measurement of joint angles during static positioning [12].

In order to assess active range of motion (AROM), researchers have used clinical observation [21], electrogoniometers [14], optoelectric motion analysis [15] as well as two-dimensional motion analysis [8]. Recently, researchers have begun to use three-dimensional (3-D) video motion analysis (henceforth referred to as video motion capture, VMC) to assess AROM. VMC produces computerized 3-D representations of skin markers and allows for continuous quantification of body segment, joint position, and movement over time [7, 9, 18]. Rash and colleagues demonstrated the validity of the VMC method in comparison to the “gold standard” 2-D lateral view fluoroscopy [30]. Research has also focused on the prehension patterns of the hand during movement tasks such as grasping plates and other commonly used objects as well as randomly shaped items [10, 25, 29, 36, 42, 44].

There are many limitations in existing studies of active hand movement with the use of VMC. In many cases, studies have been limited to analysis of some, but not all, digits and/or joints in the hand [7, 9, 18, 19, 23, 24, 32, 35, 46]. The studies contribute to the literature of active movement of the hand but it is important to address the hand as a whole since all hand muscles, bones, ligaments, tendons, and degrees of freedom (DOF) are essential for functional hand manipulation and movement. Studies on the prehension of the hand have been limited to analysis of some, but not all, digits in the hand; analysis of only the DOF necessary to complete the task; analysis of the relationship between strength, acceleration, time, velocity, and vision

throughout prehension; and the similarities and differences in prehension patterns in humans and macaques [10, 25, 29, 36, 42, 44]. These studies add to the knowledge about prehension but none have assessed the joint angles that are necessary to complete the lateral and pulp pinches. To our knowledge, no study has used VMC as a means to define all joint angles of all digits simultaneously during AROM.

The purpose of this study was to analyze all joints of all five digits while actively completing two pinches. The first hypothesis was that VMC could be used to assess the kinematics of all joints in the five digits simultaneously while performing the lateral and pulp pinches, two of the most commonly used pinch patterns in ADLs [34]. The second hypothesis was that analysis of our results would allow for development of quantitative description of the movement patterns involved in the completion of the two pinches.

Materials and Methods

Subjects

Five participants were recruited for this cross-sectional study of the lateral and pulp pinches. All participants provided informed consent. Inclusion criteria included no history of previous nerve injury to the forearm or hand, no congenital abnormalities of the upper extremity (UE), and no neuromuscular or musculoskeletal pathologies. Participants were also required to exhibit AROM of the UE within normal limits without the use of braces or orthotics. Of the five participants enrolled, one was excluded from all analyses due to unexpectedly uncoordinated movement in the absence of any known clinical condition. Of the four remaining participants, one was female and three were male, mean age was 27.5 ± 2.5 , and all were right hand dominant.

Equipment

Hand and wrist movements were captured using a VMC system (Motion Analysis Corporation, Santa Rosa, CA, USA) comprised of six 60 Hz near-infrared cameras. The working volume was calibrated to provide accuracy within 0.2 mm. Twenty-five 6-mm retro-reflective markers were placed on the skin of the dorsum of the forearm, hand, and all five digits using double-sided adhesive tape (Fig. 1). Two markers were placed on the skin of the medial and lateral aspects of the ulnar and radial styloids, respectively. Markers were secured to 24 palpable surface landmarks of the right hand and wrist as well as one in the middle of the forearm [4, 9, 35]. Marker locations were determined based on the current literature [4, 9, 35].

Fig. 1 Placement of reflective markers. Digit 1: tip, IP joint, MCP joint, CMC joint; digits 2 and 4: tip, DIP joint, PIP joint, MCP joint, and proximal metacarpal head; digits 3 and 5: tip, DIP joint, PIP joint, and MCP joint; and wrist and forearm: lateral aspect of the radial styloid and medial aspect of the ulnar styloid and middle of forearm

Testing Protocol

Subjects were seated in a chair with the right forearm resting in a fabricated splint secured to a 45° incline block (Fig. 2). This custom armrest was used to provide proper positioning and support for the participants as well as position the retro-reflective markers in view of the cameras. The splint was fabricated in a way so as to not interfere with natural biomechanical movement of the fingers throughout the pinch.

Data Processing and Analysis

EVART software (Motion Analysis Corporation) was used to capture the dynamic movement of digits during the lateral and pulp pinches. The lateral pinch occurs when the thumb is opposed to the middle phalanx of the index finger and the pulp pinch occurs when the pulp, or fleshy mass at the end of the fingers, is pressed against the pulp at the end of the

Fig. 2 Starting and end position of hand and forearm on 45° armrest with the reflective markers

thumb [27]. During each trial, subjects were instructed to fully extend and abduct the digits, in order to capture the full spectrum of motion by each digit as well as provide a common starting position to decrease the variability of starting positions, complete the given pinch (Fig. 3a, b), open their hand again to capture the full spectrum of motion by each digit, and then return to the starting position which provided a common ending position to decrease the variability of ending positions. For the lateral (Fig. 3a) and pulp pinches (Fig. 3b), a quarter attached to a wooden tongue depressor was placed within reach of the participants so as to provide a physical cue and to simulate a true pinch motion. Each participant was familiarized to the task via several practice trials.

Following data collection, marker coordinates were tracked and smoothed using a Butterworth filter with a 4-Hz cutoff (Motion Analysis Corporation). Subsequent analyses were performed in Cortex, the VMC software (Motion Analysis Corporation), Microsoft Excel, and MATLAB.

Fig. 3 **a** Lateral pinch completed with a quarter attached to a tongue depressor in order to simulate a functional pinch. **b** Pulp pinch completed with a quarter attached to a tongue depressor in order to simulate a functional pinch

Data were trimmed to isolate the pinch. Trimming began when the participant's hand was fully abducted prior to starting the pinch, as indicated in Excel by the least combined flexion of finger metacarpophalangeal (MCP) and interphalangeal (IP) joints. This position was chosen in order to provide a common starting position which would decrease the variability in starting positions. Trimming ended at the completion of the pinch (Fig. 3a, b) indicated in Excel by the last frame before the MCP and IP joints of the fingers began to extend after the pinch. The preserved data frames were then compared to the marker recordings in Cortex to verify the accuracy of the trim. All other frames recorded before or after the trimmed section were excluded from analysis.

A custom MATLAB script was used to determine two movements of the thumb carpometacarpal joint (CMC): extension (or radial abduction) and (palmar) abduction. A local coordinate system (LCS) was defined for the dorsal hand as follows: The midpoint between the second and fourth metacarpal markers was determined. The vector between this metacarpal midpoint and the third MCP joint marker defined the x -direction of the hand LCS, pointing distally. The vector between the metacarpal midpoint and the second metacarpal marker defined the y -direction of the hand LCS, pointing radially. The cross product ($y \times x$) defined the z -direction, pointing dorsally. A thumb metacarpal vector was defined by markers on the trapezium and first metacarpal-phalangeal joint. Vectors for each additional digit segment were defined by markers on their proximal and distal joints (Table 1). All joints were assessed in one DOF (flexion and extension) except the thumb CMC which was assessed in two DOF (flexion and extension; abduction and adduction).

These vectors were defined in terms of the hand LCS through a coordinate transformation matrix. The angles of the thumb vector as compared to the hand LCS in both the xz -plane (frontal plane, in the plane of the palm) and xy -plane (sagittal plane, perpendicular to the plane of the palm) were calculated. Angular data for the MCP, proximal interphalangeal joint (PIP), and distal interphalangeal joint (DIP) joints for the digits and the MCP and PIP joints for the

thumb were calculated in Excel. Vectors were created between consecutive finger markers to mathematically represent the 3-D movement of the phalanges. Angles between consecutive vectors represent the joint angles of the fingers as participants progressed through each movement. All data were normalized based on the percentage of the movement duration. Each trial was normalized by dividing each frame by the total number of frames recorded during the trial. A linear interpolation function was used to estimate joint positions at each 5 % increment for each trial. Multiple attempts were made to objectively fit explanatory curves to the data.

Results

Hypothesis 1

The total excursion range of all joints during the lateral and pulp pinches fall within the normative published/goniometric range of movement of each joint (Table 2) except CMC flexion during both pinches. The normative data suggest that the CMC joint has a maximum of 15° of flexion movement [40]. The current methods resulted in $12.9 \pm 4.1^\circ$ of CMC flexion during lateral pinch and $16.0 \pm 8.7^\circ$ of CMC flexion during pulp pinch.

Hypothesis 2

Visual analysis revealed a sigmoid pattern in all digits in both lateral and pulp pinch movements. For the purpose of this investigation, the phases were labeled initiation, preshaping, and pinch. The names were chosen to remain consistent with the current literature involving prehension patterns [10, 25, 29, 36, 42, 44]. The initiation phase was defined as the first phase, during which little to no movement occurred. The preshaping phase accounted for the majority of movement and began at the first notable increase in movement. The pinch phase began at the reduction in slope as movement came to a stop.

Table 1 Definition of vectors using proximal and distal joints. Vectors were created between consecutive finger markers to mathematically represent the 3-D movement of the phalanges and these angles

Proximal marker (x, y, z)	→	Distal marker (x, y, z)	=	Digit segment (x, y, z)
Thumb metacarpophalangeal joint	→	Thumb interphalangeal joint	=	Thumb proximal phalanx
Thumb interphalangeal joint	→	Thumb tip	=	Thumb distal phalanx
Finger metacarpophalangeal joint	→	Finger proximal interphalangeal joint	=	Finger proximal phalanx
Finger proximal interphalangeal joint	→	Finger distal interphalangeal joint	=	Finger middle phalanx
Finger distal interphalangeal joint	→	Finger tip	=	Finger distal phalanx

represent the joint angles of the fingers as participants progressed through each pinch pattern

Table 2 Mean (standard deviation) ROM of participants and normative data

	Pulp pinch digit 1	Pulp pinch digits 2–5	Lateral pinch digit 1	Lateral pinch digits 2–5	Normative data digit 1	Normative data digits 2–5
Carpometacarpal joint flexion	16.0 (8.7)		12.9 (4.1)		15	
Carpometacarpal joint abduction	13.8 (17.1)		22.9 (7.8)		60	
Metacarpophalangeal joint flexion	11.1 (3.8)	38.7 (1.6)	17.9 (4.3)	48.5 (7.1)	50	90
Proximal interphalangeal joint flexion	23.0 (20.2)	25.7 (15.3)	45.5 (18.8)	72.6 (9.4)	90	120
Distal interphalangeal joint flexion		11.8 (4.0)		35.5 (9.2)		80

Note: The carpometacarpal joint is anatomically exclusive to digit 1. In the case of digit 1, proximal interphalangeal flexion refers to interphalangeal flexion

Figure 4 represents the fourth PIP joint of one exemplar participant during the lateral pinch. All participants and all the remaining joints follow the same sigmoid pattern in completing the lateral pinch. Figure 5 represents the second MCP of one exemplar participant during the pulp pinch. Once again, all participants and all joints followed the same sigmoid pattern in completing the pulp pinch. Analysis of the sigmoid movement curves revealed three phases during the movement cycle of both the lateral and pulp pinches.

Multiple attempts were made at objectively identifying the transition points of the three phases. First, a fourth-order polynomial was fit to the data. The roots of the second derivative of this polynomial represent the inflection points of the curve and were used as an estimation of the transition points between phases. Next, piecewise linear regression with two “knots,” or breakpoints between linear fits (PLR 2), was attempted to automatically identify the transition points while minimizing r -squared [13]. Finally, piecewise linear regression with one knot (PLR 1) was attempted separately over two halves of the data in order to automatically calculate the transition points within acceptable constraint boundaries [13]. It was determined that these methods were unreliable in estimating the phase transitions within visually acceptable limits.

Fig. 4 Lateral pinch: one exemplar participant 4 proximal interphalangeal joint. Vertical lines mark beginning of preshaping and pinch phase

As a result, two independent raters subjectively identified the inflection points. The independent raters agreed within 10 % of the movement cycle 80.5 % of the time with the lateral pinch and 56.3 % of the time with the pulp pinch. The independent raters conferred on their protocol for determining the inflection point locations of the pulp pinch and determined errors. After conferring, the independent raters re-assessed the pulp data and agreed almost 100 % of the time. The raters then conferred on the remaining cases of disagreement to identify the transition points.

The mean movement cycle of the lateral pinch is illustrated in Fig. 6a. During the completion of the lateral pinch, movement generally progressed from the ulnar to the radial side of the hand as indicated by the smallest percentage of the movement cycle spent in the initiation phase. Movement starts with digits 2 to 4 and digit 1 is the last digit to begin the preshaping phase. The IP and CMC joints of digit 1 are the last two joints to become engaged in the preshaping phase indicated by the largest percentage of the movement cycle being spent in the initiation phase. The first digit to have all joints actively engaged in the preshaping phase is digit 4 followed by digits 3, 5, 2, and finally digit 1. For the completion of the lateral pinch, once again movement progresses in an ulnar to radial pattern (Fig. 6b). Digits 2 to 5

Fig. 5 Pulp pinch: one exemplar participant 2 metacarpophalangeal joint. Vertical lines mark beginning of preshaping and pinch phase

Fig. 6 Lateral pinch phase durations in terms of percentage of the movement cycle, average of all participants. Joints are organized by relative length of the initiation phase (a) and the completion phase (b). The preshaping (a) and pinch (b) phases generally progress from more ulnar to more radial digits, and the thumb is the last digit to begin the preshaping and pinch phases. Gray bar, initiation; fine hatched bar, preshaping; hatched bar, pinch

enter the pinch phase before digit 1 as indicated by the large percentage of the movement cycle being spent in a static position in the pinch phase (Fig. 6b). All of the joints of digit 5 progress into a static position prior to any other digits indicating that it is the first digit to stop the preshaping phase and enter into the pinch phase (Fig. 6b). The other digits progress into the pinch phase in the following manner: digits 4, 2, 3, and finally digit 1. Digit 1 is the last digit to have all of its joints come to a static position.

During the completion of the pulp pinch, the preshaping phase begins in a proximal to distal pattern (Fig. 7a). Movement progresses from the MCP joint of digits 1 to 5 to PIP/IP joint of digits 1 to 5 and finally to the DIP joints of digits 2 to 5 (Fig. 7a). The first digit to have all joints actively engaged in the preshaping phase is digit 2 followed by digits 1, 4, 5, and finally digit 3. The preshaping phase

Fig. 7 Pulp pinch phase durations in terms of percentage of the movement cycle, average of all participants. Joints are organized by relative length of the initiation phase (a) and the pinch phase (b). The preshaping (a) and pinch phases (b) generally progress from more proximal to more distal joints. Gray bar, initiation; fine hatched bar, preshaping; hatched bar, pinch

ends in a proximal to distal pattern for digits 2 to 5 with the exception of digit 1 (Fig. 7b). Movement ends in the MCP of digits 2 to 5, progressing to the PIP/IP of digits 1 to 5. The last joints to become actively involved in the preshaping phase are the DIP joints of digits 2 to 5 and the MCP of digit 1. The first digit to have all joints enter the pinch phase is digit 1 followed by digits 4, 2, 3, and finally digit 5.

Discussion

The VMC system has been shown to be a reliable way to assess AROM of multiple joints simultaneously [30] in studies of the hand. In the past, application of this system has been limited to the study of some, but not all, fingers

and/or joints. This study is the first to assess all joints of all five digits simultaneously through AROM of two common methods of pinch. Our results confirmed the feasibility of the VMC system in quantification of joint angles during active movement. Confirmation of previously identified movement patterns suggests convergent validity of the VMC method. With the exception of thumb CMC flexion, all of the means ($\pm$ SD) (Table 2) of all the joints of the lateral and pulp pinch fall within the normative data of both pinches. Furthermore, our results indicated that movement was not overestimated during the completion of the pinch patterns. One does not expect the joints to meet or surpass their maximum possible excursion while completing the lateral and pulp pinches as both are submaximal activities. The normative data state that the CMC joint has a maximum of 15° of flexion [40]. Our measurements of the CMC joint may exceed these values by as much as 9.7° for the pulp pinch and 2° for the lateral pinch. Flexion of the CMC joint for both the lateral and pulp pinches was the only joint movement that exceeded the normative data, and due to the wide standard deviation, it should not be considered a meaningful difference. It is important to note that all but one participant fell within the normative data for CMC flexion of the lateral pinch. The participant who was above the normative sample surpassed it by 2° . The participant would still be within the normative data if the 3° to 5° of error is taken into account [28]. In regards to CMC flexion during the pulp pinch, two participants fell 6° to 7° below the normative sample and two participants surpassed the normative sample by 8.5° and 8.7° [30]. This could be due to hypermobility of the CMC joint of the two participants who surpassed the normative sample. The VMC system is very accurate [30] and is thus more likely to detect even slight differences in joint angles which is indicated by the wide standard deviation.

We discovered three distinct phases that the joints progress through during the completion of the lateral and pulp pinches, which we termed the initiation phase, the preshaping phase, and the pinch phase. The initiation phase was defined as the first phase, during which little to no movement occurred. The preshaping phase accounted for the majority of movement and began at the first notable increase in movement. The pinch phase began at the reduction in slope as movement came to a stop. In the lateral pinch, digits 2 to 5 are the first digits to begin and complete the movement cycle. The thumb is the last digit to begin the preshaping phase as well as the last digit to enter the pinch phase. This signifies that the thumb is the digit that completes the lateral pinch because digits 2 to 5 are in a static position when the thumb is still moving in order to complete the pinch. When examining the phases of the digits, it can be noted that the index finger is also the last to complete the movement cycle. This is important to note because the index

and thumb are the two principal fingers involved in the lateral pinch which may account for this observed delay of the pinch phase. When completing the lateral pinch, individuals need greater accuracy in the positioning of the joints of the thumb and index finger to successfully complete the pinch.

The pulp pinch possesses the same three phases as the lateral pinch throughout the entire movement cycle but the pattern within those phases is not as clear as the lateral pinch. The joints of the digits do not move together, but in general, the joints begin and end the movement cycle in a proximal to distal pattern. The MCPs and PIPs are the first joints to begin and end the movement cycle. The DIP joints are the last joints to begin and end the movement cycle. When examining the movement of the joints during the pulp pinch, it is important to note that it is expected that the MCPs begin the preshaping phase first since the MCPs are the joint that does the most flexion and must start moving earlier than the other joints in order to bring the more distal joints towards the thumb in order to complete the pinch.

VMC is not only valid in the quantification of joints (as demonstrated by comparison to the normative measures) but also captures the dynamic movement which we can observe visually but thus far have not had a means of objectively quantifying. VMC provides a means to assess active movement during ADLs and IADLs.

The limitations to this study include small sample size, young age of the participants, no goniometric or strength measurements of the participants, the subjectivity of the independent raters, human error when applying the retro-reflective markers, as well as the possibility of skin movement during the completion of the pinch which could skew the data collected from the retro-reflective markers. Measurements of each joint's maximum excursion during AROM would have been beneficial to help compare them to the normative data [40] prior to the collection of the data. Hypermobility may explain excessive flexion of the CMC joint during the pinches, but without goniometric measurements we cannot determine if that is the case. Measurements of the participant's strength used to complete the pinches would have been beneficial to compare them to the normative data [26] prior to the collection of the data. Due to the mathematical equations not fitting the data points, two independent raters subjectively identified the points of inflection. The independent raters agreed within 10 % of the movement cycle 80.5 % of the time with the lateral pinch and almost 100 % of the time with the pulp pinch. The raters conferred on cases of disagreement to identify the remaining transition points. Although they agreed more than 80 % of the time, this subjective method is inherently prone to human error.

VMC provides a means to assess all the joints of the hand simultaneously during the completion of two commonly

used pinches as well as other functional activities. VMC can be adapted to study a vast array of ADLs and IADL by easily adapting the number and angles of cameras as well as marker placement. Researchers may be able to use this method in order to determine specific contributors to a movement deficit. By clarifying the deficit, the researchers can publish their findings that will help clinicians target interventions to help remediate a specific area which could make the rehabilitation process shorter. This could also lead to a quicker recovery of function due to therapy targeted to a specific deficit.

The method developed for this study will provide researchers the means to measure joint angles of the hand simultaneously throughout AROM. The method created for this study will be used in current and future studies in the Human Performance Lab. The method is critical to the completion of current studies involving participants with spinal cord injuries, brachial plexus injuries, and nerve transfers. These studies include diverse injuries to various nerves and muscles which have previously made the measurement of the participant's AROM difficult to assess. This method will allow researchers to focus on the implications of injury, surgery, and therapy for functional gain.

This study provides the only information about AROM of all joints of the hand simultaneously while completing the lateral and pulp pinches. It was determined that there were three phases that the digits progress through during the completion of the pinch. Those patterns were clearer during lateral pinch than during pulp pinch. The thumb is the last digit to complete the lateral pinch. The pulp pinch had a general pattern of proximal to distal movement.

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