Dynamic Functional Assessment of Hand Motion Using an Animation Glove: The Effect of Stenosing Tenosynovitis

HAND
2018, Vol. 13(6) 695–704
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DOI: 10.1177/1558944717729218
hand.sagepub.com

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Abstract

Background: The aim of the present study is to determine whether an animation glove can be utilized to provide a reliable and reproducible assessment of dynamic hand function and whether this assessment is altered in the setting of hand pathology. **Methods:** Ten subjects without known hand pathology and 11 subjects with known stenosing tenosynovitis were assessed on tasks involving hand function at varied speeds, including forceful and gradual making of a fist and the quick and slow grip of a baseball using an animation glove to record range of motion and measures of velocity (CyberGlove II). **Results:** In normal subjects, peak extension and flexion velocity of the index and middle finger was highest in the metacarpophalangeal and lowest in the distal interphalangeal; however, the converse was true in the ring finger. In those subjects with stenosing tenosynovitis, the animation glove was able to detect a triggering event during assessment. Furthermore, there was a significant decrease in the maximum velocity of the proximal interphalangeal joint observed with the slow fist task in both flexion and extension (55%, $P < .01$) in the affected hand when compared with the unaffected hand. **Conclusions:** The CyberGlove II can be utilized in the dynamic functional analysis of the hand and is able to detect a triggering event in subjects with known stenosing tenosynovitis. Those subjects demonstrate a significant decrease in maximum velocity in slow fist tasks, highlighting the need for comprehensive assessment to ascertain the full extent of functional limitations that can occur in the setting of hand pathology.

Keywords: CyberGlove, functional assessment, hand, dynamic motion, trigger finger

Introduction

Functional assessment of hand motion is important in the evaluation of pre- and postsurgical function as well as work-related evaluations. Most functional assessments focus on static measurements, using goniometry and grip/pinch strength devices; however, these tests may not accurately reflect function, given that these tests do not account for the use of muscle substitution and inventiveness observed in patients with pathological hand conditions.¹ A more accurate representation of hand function may be the use of dynamic evaluation of motion and assessment of global function in the hand using real-world tasks. Furthermore, this assessment may reveal new parameters that are more accurate and relevant for daily activities of daily living (ADLs). In the current study, a battery of assessable tasks were developed using the CyberGlove II (CyberGlove Systems LLC, San Jose, California) and were performed by healthy volunteers. We hypothesized that utilization of the CyberGlove II would

allow for assessment of these tasks in real time and thus would produce a reproducible baseline function level.

Functional assessment becomes more critical in the setting of hand pathology. Stenosing tenosynovitis, trigger finger, is the most common tendinopathy in the hand and wrist. An underreported condition, it occurs in approximately

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Supplemental material is available in the online version of the article.

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2.2% of the general population, a number that increases to 10% to 20% in diabetic patients. Initial treatments include night splinting, nonsteroidal anti-inflammatory drugs, activity modification, and aggressive physical therapy with excellent outcomes. However, in the setting of recurrence, more often observed in those with diabetes, multiple affected digits, or other associated tendinopathies, corticosteroid injections are considered, which have also demonstrated excellent results. If nonoperative methods fail, release of the A1 pulley may be required for symptomatic improvement. However, as mentioned above, functional assessment of finger motion is generally based on static methods. In the present study, we aimed to examine subjects with known stenosing tenosynovitis to determine whether the animation glove could detect a triggering event and whether there are other variables altered in these patients with trigger finger that could be evaluated during progression of physical therapy to assess its success.

Materials and Methods

Subject Recruitment

Ten healthy male volunteer test subjects ranging in age from 23 to 54 years were recruited for enrollment in this institutional review board (IRB)-approved study. Nine subjects were right-hand dominant, and 1 subject was left-hand dominant. All subjects were without hand pathology. The second study consisted of 9 patients with 11 fingers with known stenosing tenosynovitis of the index, middle, or ring fingers recruited from the clinic of one board-certified hand surgeon. Subjects ranged in age from 47 to 74 years (5 men, 4 women), with a total of 11 fingers with stenosing tenosynovitis (1 index, 4 middle, and 6 ring fingers). Subjects underwent testing with the affected and unaffected hand. All studies were approved through our IRB, and all procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008 (5). Informed consent was obtained from all patients for being included in the study.

Dynamic Testing

Subjects were assessed on 2 basic tasks involving normal hand function at varied speeds. Tasks included: (1) the forceful making of a fist; (2) the gradual making of a fist; (3) quickly grasping a regulation size baseball (circumference 231 mm, Rawlings, St Louis, Missouri); and (4) more slowly grasping the baseball. During the fast exercises, subjects were instructed to perform the task as quickly/forcefully as possible. The slower analog of the task was performed at a self-selected, slower speed in a smooth motion. Each task was performed 10 times in both the right and left hands.

Figure 1. CyberGlove II with placement of sensors. Position of actual and calculated sensor positions in the right hand 18-sensor CyberGlove II. Sensor positions are calculated at the DIP joint for the index through small fingers. Symmetric gloves were used for data collection.

Data were captured using the CyberGlove II, an animation glove previously used for computer graphics development which allows for dynamic motion capture. The glove uses resistive bend-sensing technology to convert hand and finger motions into digital, real-time, joint-angle data. Each glove is equipped with sensors that capture interphalangeal (IP) joint range of motion, metacarpophalangeal (MCP) joint range of motion, and motion between the rays in the coronal plane (Figure 1). The 18-sensor CyberGlove II model was used, which features 2 bend sensors on each finger and the thumb, 4 abduction sensors, a palmar arch sensor, and sensors to measure thumb adduction and wrist flexion/extension. A computer algorithm is used to calculate distal interphalangeal (DIP) joint position based on the position of the other sensors.

All data acquisition was performed by one individual. The process began with glove calibration for the subject. This involved voluntary assumption of the “ok sign” and “flat palm” positions with researcher confirmation of the correct positioning of the virtual hand on a computer screen (Figures 2a and 2b). Offset and gain values were then adjusted for each joint such that the virtual model accurately reflected the test subject’s hand. The subject’s view of the hand was blocked using an opaque surface to prevent visual feedback. After calibration, tasks were performed 10 times, and joint movement and the time taken to perform each repetition of the task were recorded in degrees and seconds,

Figure 2. CyberGlove II software representation of tasks. “Ok” (a) and “flat palm” (b) sign as represented in real time using CyberGlove II software after calibration is complete.

respectively. Data were collected at 90 Hz as a string of coordinates in the form “Time, Angular Position.” Position and angular velocity were determined based on the change in finger position over time; in this setting, the term “velocity” is referring to angular velocity. The mean velocity of each joint analyzed was found by averaging 10 instances of flexion and 10 instances of extension per test. The results of each test subject were pooled together for final analysis. The data were then normalized by finding the ratio between the maximum velocity and average velocity of the joint of interest. This ratio represents the relationship between how fast a joint moves and the average velocity over the full duration of movement. Normalization was performed to compare the mean and peak velocities among subjects, taking into account variations in velocity. The MCP, proximal interphalangeal (PIP), and DIP joints of the index, middle, and ring fingers were examined in this manner.

Calibration of Angular Measurements

The current gold standard for hand function is goniometric measurement of total active motion of the MCP, PIP, and DIP joints. One subject had the CyberGlove II calibrated as described above and underwent angular analysis in 3 positions—flat palm, full fist, and intrinsic plus position. At each position, the angular measurements using the CyberGlove II and a traditional goniometer were recorded

(Supplemental Table 1). It should be noted that the goniometer measurements were performed while the CyberGlove II was worn and therefore may be less accurate than a bare hand; however, this method ensured the exact same positioning of the fingers for assessment. When directly comparing measurements made with the CyberGlove II and static goniometer measurements, we calculated that even with the presence of artifact, the average deviation between measurements was 11°.

Statistical Analysis

Data were initially analyzed to ensure normal distribution (MatLAB 2012b, Natick, Massachusetts). Once this was confirmed, an unpaired Student *t* test (GraphPad Prism, La Jolla, California) was utilized to analyze differences and *P* < .05 was considered significant.

Results

CyberGlove Assessment of Dynamic Function in Normal Patients

All subjects were able to complete the tasks efficiently using either hand. Data are summarized in Table 1. A position vs time curve representative of all of the joints in flexion and extension was generated (Figures 3a and 3b). The figure

Table 1. Slow and Fast Fist Extension and Flexion Velocity in Finger Joints.

Slow fist extension and flexion velocity				
	Mean extension velocity slow	Peak extension velocity slow	Mean flexion velocity slow	Peak flexion velocity slow
	Degrees/second	Degrees/second	Degrees/second	Degrees/second
Measured				
Index				
MCP	176.14	367.29	170.35	380.35
PIP	196.05	412.43	201.21	443.58
DIP	89.46	209.36	68.01	178.18
Middle				
MCP	183.75	374.72	183.19	371.93
PIP	82.18	142.62	87.66	156.86
DIP	94.08	221.05	84.81	211.32
Ring				
MCP	86.50	151.94	77.26	142.66
PIP	156.53	398.70	140.93	353.43
DIP	103.92	204.68	117.06	206.05
Normalized				
Index				
MCP	0.50	1.00	0.47	1.00
PIP	0.51	1.00	0.48	1.00
DIP	0.45	1.00	0.41	1.00
Middle				
MCP	0.52	1.00	0.50	1.00
PIP	0.57	1.00	0.56	1.00
DIP	0.46	1.00	0.44	1.00
Ring				
MCP	0.59	1.00	0.54	1.00
PIP	0.43	1.00	0.43	1.00
DIP	0.55	1.00	0.58	1.00
Fast fist extension and flexion velocity				
	Mean extension velocity fast	Peak extension velocity fast	Mean flexion velocity fast	Peak flexion velocity fast
	Degrees/second	Degrees/second	Degrees/second	Degrees/second
Measured				
Index				
MCP	495.13	989.82	406.04	946.25
PIP	444.51	953.06	475.65	949.69
DIP	256.21	574.21	199.26	466.96
Middle				
MCP	400.87	870.21	442.23	816.30
PIP	242.33	524.52	254.89	464.19
DIP	262.24	546.52	218.25	531.75
Ring				
MCP	179.95	343.25	129.51	269.70
PIP	416.99	870.37	375.55	829.94
DIP	230.89	472.74	285.89	491.30

(continued)

Table 1. (continued)

Fast fist extension and flexion velocity

	Mean extension velocity fast	Peak extension velocity fast	Mean flexion velocity fast	Peak flexion velocity fast
	Degrees/second	Degrees/second	Degrees/second	Degrees/second
Normalized				
Index				
MCP	0.50	1.00	0.44	1.00
PIP	0.46	1.00	0.50	1.00
DIP	0.44	1.00	0.44	1.00
Middle				
MCP	0.45	1.00	0.53	1.00
PIP	0.49	1.00	0.57	1.00
DIP	0.48	1.00	0.41	1.00
Ring				
MCP	0.54	1.00	0.51	1.00
PIP	0.49	1.00	0.44	1.00
DIP	0.49	1.00	0.59	1.00

Note. MCP = metacarpophalangeal; PIP = proximal interphalangeal; DIP = distal interphalangeal.

demonstrates the change in degree of one joint over a single interval of flexion/extension during fist making. During fist making in flexion, maximum velocity occurred over 61° to 19° (71% of arc of motion). In extension, maximum velocity occurred over 24° to 51° (46% of arc of motion) of extension.

In the fast fist task, maximum extension velocity for the index finger was 990°/s (mean 495°/s) at the MCP joint, 953°/s (mean 445°/s) at the PIP joint, and 574°/s (mean 256°/s) at the DIP joint (Figure 3c). Index finger flexion during the same task demonstrated a peak velocity of 946°/s (mean 406°/s) at the MCP joint, 950°/s (mean 476°/s) at the PIP joint and 467°/s (mean 199°/s), at the DIP joint (Figure 3d).

When normalized to the maximum velocity at each respective joint, the average speed of flexion and extension in the index finger joints was roughly half of the peak velocity achieved during the making of the fastest possible fist (Figures 3e and 3f). In the same fast fist making task, middle and ring finger velocities followed the same trend as the index, with average velocities roughly half the value of peak velocities achieved in this task (Table 1).

Similar patterns emerged when patients underwent analysis making a slow fist in that mean velocity of each digit was approximately half of the peak velocity (Figures 3e and 3f). The peak extension velocity of the index PIP joint was the highest (412°/s, mean 196°/s) when compared with the MCP joint (367°/s, mean 176°/s) and the DIP (209°/s, mean 89°/s). Furthermore, flexion velocity of the PIP, MCP, and DIP joints were similar to that which was observed with extension

(444°/s, 380°/s, and 178°/s, respectively.) This pattern was observed with both the middle and ring fingers (Table 1).

CyberGlove Detection of Somatosensory Response Time

During the task when subjects were to grasp a ball, a predictable deceleration of joint motion was observed prior to initiation of ball contact (Figure 4). The mean joint breaking time was 92 ms for the MCP joint and 82 ms and 81 ms for the PIP and DIP joints, respectively. The angular change over which fist breaking occurred is also depicted in Figure 4 (red lines). The MCP joint ranged 2.82° before stopping after achieving peak velocity in grasping the ball. PIP joint and DIP joint range in stopping flexion were 3.51° and 3.31°, respectively.

Dynamic Assessment of Patients With Stenosing Tenosynovitis Using the CyberGlove

Patients with known stenosing tenosynovitis underwent the fast/slow fist tasks as described previously utilizing their affected and unaffected hand. Peak velocities obtained from the unaffected hand are similar to those observed in the control subjects. As seen in Figure 5, the CyberGlove was able to detect a triggering event in all subjects assessed (Figure 5b demonstrates a representative curve in the setting of no known hand pathology).

Figure 3. Extension and flexion characteristic curves and velocity measurements.

Note. Characteristic curves of extension (a) and flexion (b) demonstrate maximum (dashed lines) and mean (dotted lines) velocities are plotted over joint position (black line) during joint movements. In addition, bar graphs demonstrate peak and average extension and flexion (c and d, respectively) velocities for the slow fist (mean—white bars, peak—light gray bars) and fast fist (mean—dark gray bars, peak—black bars) tasks. Normalized measurements of extension (e) and flexion (f) of joints. Data are representative of mean velocity normalized to peak velocity for slow fist (white bars) and fast fist (black bars) tasks. MCP = metacarpophalangeal; PIP = proximal interphalangeal; DIP = distal interphalangeal.

During the fast fist task, there were no differences between the peak flexion velocity ($564^{\circ}/s$ vs $600^{\circ}/s$) or extension velocity ($810^{\circ}/s$ vs $752^{\circ}/s$) in the affected hand compared with the unaffected hand (Figure 6). As before, the mean velocity was approximately 50% of the peak velocity and was not altered in the setting of pathology (data not shown). On the other hand, there was a significant decrease in the peak flexion ($126^{\circ}/s$ vs $288^{\circ}/s$, $P = .008$) and extension ($155^{\circ}/s$ and $338^{\circ}/s$, $P = .0023$) velocity in the slow fist task in the setting of stenosing tenosynovitis.

Discussion

The present study demonstrates that an animation glove, such as the CyberGlove II, can be utilized for functional assessment of the hand. Furthermore, the study demonstrates that ability of the CyberGlove II to detect a triggering event in patients with stenosing tenosynovitis. Finally, the study also demonstrates that there is a significant decrease in the peak velocity with flexion and extension of the digits in patients with trigger finger when undergoing

slow tasks, a finding that highlights the need for comprehensive functional assessment of hand function when identifying and treating various forms of hand pathology.

Dynamic assessment of hand and finger function has been examined in the literature through the use of motion capture technology.^{2,4,5,7,9,10} Many of these studies focus on the kinematics of the thumb where range of motion assessment has been performed on healthy subjects and those with hand pathology.^{4,5,10} Marquardt et al noted that patients with carpal tunnel syndrome (CTS) exhibited less functional thumb range of motion, but maintained pinch strength.⁵ This finding highlights the necessity for dynamic functional assessment, given that a static test such as grip strength was not altered in patients with CTS. While dynamic assessment of the thumb has been well studied, there is a paucity of data on the dynamic assessment of the fingers, as examined in the current study. Given that some individuals lack a superficial flexor to the small finger,⁸ the current analysis was focused on the index, middle, and ring fingers. The CyberGlove II has been previously utilized to analyze finger joint motion³; however, the present study is the first of its kind to

Figure 4. Representative trace for somatosensory feedback for one subject while performing the baseball grasping task (see text for task details).

Note. Individual joint motions are depicted for the MCP joint, PIP joint, and DIP joint. The point at which ball contact occurred is indicated by the start of oscillations in motions likely due to somatosensory feedback (solid black line). Using the slope of oscillations, a braking speed, braking time, and angular braking distance are demonstrated. MCP = metacarpophalangeal; PIP = proximal interphalangeal; DIP = distal interphalangeal.

Figure 5. Effect of trigger finger on joint velocity utilizing the CyberGlove.

Note. (a) Individual normalized range of motion results for extension in patients with known trigger finger; the trigger event is outlined in a black box. See Figure 4. (b) Representative plot for normal range of motion of a finger without known pathology.

Figure 6. Rotational speed of trigger digit versus control digit.

Note. Peak rotational velocity for the PIP joint in control patients ($n = 9$, white bars) and those with known trigger finger ($n = 10-11$, black bars) during fast and slow flexion and extension tasks. See Figure 4. Results are mean $\pm$ standard error of the mean (SEM).

* $p < .01$ vs control digit.

determine whether the measurements of finger velocity translate into a functional assessment and whether these measurements are altered in the setting of hand pathology.

The previous gold standard for functional assessment involves goniometry; however, the current study demonstrates that the use of joint velocity as a novel parameter for functional assessment. In the current study, the ratio of mean to peak velocity was extremely consistent (0.5 for flexion and extension) across joints and fingers in patients without known pathology. These measurements reveal a contribution of acceleration and deceleration to the average joint velocity. Despite the variation of angular velocities observed in flexion and extension in Figures 3c and 3d, some consistencies among subjects emerged. First and foremost, acceleration and deceleration occurred over roughly the same duration of flexion and extension. Furthermore, we found that the maximum velocity for both flexion and extension occurred over a range of time for both flexion and extension, a finding that suggests once peak velocity is achieved, it is maintained over a similar period of time. Furthermore, it is important to note that there was no learning behavior exhibited in any of our patients; the observations of decelerations remained consistent throughout trials. Thus, the use of this ratio between mean to peak velocity may allow for the analysis of subject effort, an important concern in functional assessment of hand function that is difficult to discern using current methods.

The current study was revealing in its analysis of joint velocity of the MCP, PIP, and DIP joints in the index, middle, and ring fingers. While the index and middle fingers were similar in that the more proximal MCP joint reached higher velocities than the more distal PIP and DIP joints, the ring finger was the opposite in that the PIP and DIP joint velocities were consistently higher than the MCP joint. This

finding would suggest a disparate recruitment of radial versus ulnar sided digits when performing the functional tests in the present study. In agreement with this, others suggested that the ulnar digits play a more crucial role in grip strength, with a loss of up to 54% of strength of grip with neutralization of the ring and small fingers.⁶

Interestingly, similar patterns in joint motion occurred in patients with known trigger finger in that when comparing the joint velocity of the MCP and PIP joints in the middle and ring fingers. The peak velocity of the MCP joint was higher compared with the PIP joint in middle finger of affected and unaffected hands, while the peak velocity of the PIP joint was higher in the ring finger of the same patients. This would suggest that the pattern of recruitment of joint function is not altered in the setting of stenosing tenosynovitis. Furthermore, the ratio of peak to mean velocity was similar to that seen in the study performed on control patients, a finding that suggests that trigger finger does not affect the ratio of peak to mean velocity. Despite this, the CyberGlove II was able to detect a triggering event in all of these patients during assessment. Thus, there remains a possibility that the dynamic signature of a triggering event could be developed into an algorithm allowing for a more automatic approach to the diagnosis of stenosing tenosynovitis. Further studies are required to determine whether the CyberGlove II is able to detect predictable dynamic patterns in other hand pathologies. Interestingly, there was a significant decrease in the peak velocity in those hands with trigger fingers compared with their unaffected hands; however, this was only demonstrated when performing slow tasks. Taken together, these findings suggest the utility of comprehensive dynamic functional assessment to determine the alterations that occur in the presence of hand pathology.

The current study does have limitations. There were differences observed in the angular measurements when comparing angles using the gold standard of goniometry and the CyberGlove II. However, as testing of subjects continued, it became apparent that velocity measurements provided a more accurate and useful measurement of hand function, allowing for assessment over a wide range of positions. Consequently, the authors chose to focus on the dynamic velocity measurements obtained from the CyberGlove II instead of static angular measurements with either method. Another limitation is that the 18-sensor CyberGlove model used in the present study does not measure DIP motion directly and thus our measurements of DIP velocity have been calculated. However, similar conclusions can be drawn based on the data obtained from MCP and PIP joints directly measured using this CyberGlove model. In addition, preliminary evidence suggested that measurements of DIP velocity using an alternative 22-sensor CyberGlove were inaccurate; thus, the 18-sensor model was utilized in the current study. Another limitation is that there was significant variability among subjects regarding the slow tasks performed, as each subject's interpretation of relaxed motion differed. However, it is important to include data incorporating self-selected slow tasks for comparison to tasks performed at maximum speed given that not all functional tasks in ADLs require finger motion at maximal speed. Furthermore, despite the significant variability between patients, the ratio between maximum and average velocity remained the same. More importantly, it was these self-selected slow tasks that revealed some of the functional deficiencies in the setting of trigger finger, a finding that would not have been revealed examining tasks solely at maximum speed—and patients invariably use effort to alter readouts of other hand assessment modalities. This finding highlights the need for comprehensive dynamic assessment of finger velocity to fully appreciate the alterations that occur in the setting of various hand pathologies. Finally, the study size was small: 10 patients in the control study and 11 patients with known trigger finger. However, it should be noted that our study was adequately powerful, and the number of subjects examined in the current study is similar to other recent reports examining hand function kinematics.^{4,5}

In conclusion, the present study demonstrates the utility of using an animation glove for dynamic assessment of hand and finger function. Furthermore, the present study highlights the utility of using a novel parameter, velocity, to assess hand function. Furthermore, our data on patients with known stenosing tenosynovitis demonstrate both the utility of an animation glove to identify hand pathology as well as its ability to assess functional deficiencies when performing dynamic tasks. Data using these methods could be utilized in a clinical setting to evaluate injury and functional

recovery. Furthermore, the analysis performed here may be sensitive enough to assess the role of effort in functional assessment. Finally, previous studies determining functional deficiencies in hand pathology, such as trigger finger, are cumbersome and would be difficult to incorporate into a clinical setting⁹; however, the CyberGlove II provides a reproducible and predictable method of dynamic hand function assessment that could be easily utilized to assess patients in a clinical setting.

Acknowledgments

The authors would like to acknowledge Rachel Johnston for her assistance in manuscript preparation. In addition, the authors would like to acknowledge Faisal Yasadi (CyberGlove Systems, San Jose, California) for his technical assistance regarding the CyberGlove II.

Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

The institutional review board approved this study, and consent was obtained from all participants involved.

Statement of Informed Consent

Informed consent was obtained from all individual participants in the study.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no industry financial support for the research, authorship, and/or publication of this article. The senior author, JE, has been supported by NIH 1 K08 AR060164-01A and DOD W81XWH-16-1-0725, as well as the American Society/Foundation for Surgery of the Hand "Hand Surgeon Scientist Award".

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