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Sensor based System for Hand Function Assessment: Review Paper

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Abstract

For assessments of hand function, it is crucial, mostly in the medical field, to record hand motions. For testing manual dexterity and rehabilitation, many data gloves have indeed been created. Regarding the sensor technique used, evaluation methodologies, and reasons, this article review intends to study and assess the features of technology-assisted hand evaluations and their uses. This study seeks to facilitate the design and translation of technology-aided hand functional assessment to clinical practice in accordance with the inadequacies of present applications and current alternatives afforded by upcoming methods. A number of previous studies (from 2012 to 2021) were relied upon to conduct a research study of the most important techniques used in analyzing and evaluating hand movement. The sensing technologies that are most frequently employed for kinematic and kinetic analysis are force sensing resistors (FSR) and inertial measurement units (IMU).

Keywords: Activity of daily living, Hand assessment, Hand kinematics, IMU, Instrumented glove.

1. Introduction

The hand's intricate anatomy is expertly designed to perform a number of challenging activities that are necessary for daily activity. The grasping capability of the hand and move objects is necessary for people in the creation of daily activities. A crucial aspect of this capability is the hand's muscular and kinematic complexity, which includes more than 38 muscles, both intrinsic (in the hand) and extrinsic (in the forearm), controlling over than 25 degrees of freedom (DoF) **[1]**. Numerous injuries and traumas can impair hand physiological performance, which can have major to minor functional effects on everyday activities. Events that are considered pathological include severe injuries, rheumatic diseases, metabolic abnormalities, and neurological conditions, can significantly reduce a person's capacity to carry out daily tasks, which has an impact on their ability to engage in social activities and their quality of life in terms of their health **[2,3]**. Only in the United States, over 700,000 individuals have a stroke every year, and almost two out of every three of these people survived the stroke and need some type of motor treatment, which typically emphasizes hand motion and control. The World Health Organization (WHO) predicts that 15 million individuals suffer from strokes annually **[4]**. In addition, each year, roughly 12,500 Americans survive spinal cord injuries (SCI), and the SCI population in 2016 was projected to be 276,000 persons, or 906 every million people **[5]**. Traditional approaches for hand functional assessment focus on subjective assessments, which are insensitive to subtle variations in impairments **[6]**. Traditional clinical assessments for measuring upper limb functionality, such as the Wolf Motor Function Test (WMFT) and the Action Research Arm Test (ARAT), place a strong focus on task completion rather than kinematics **[7]**. Dynamic recordings of fingers flexing in gloves during expert tasks such as grabbing items are achievable utilizing three-dimensional motion capture devices as well as instrumented gloves. Because they are big, 3D motion capture devices are less appropriate for frequent clinical applications. Numerous instrumented gloves have been created since the late 1970s in industry and academia for use in a variety of industries and areas, including virtual reality, computer gaming, and sign language interpretation, medical, robotics and rehabilitation. These gloves were created using a variety of sensing technologies, as stated by Dipietro et al. **[8]**. With a purpose to satisfy as a source of motivation for the development of future technologies, this systematic overview of the most recent technology-based methodologies for a quantitative assessment of hand functionality is offered. The review categorizes systems according to their technology, features of measuring, methods of evaluation, as well as purposes in order to give a summary of the available sensing methods for evaluating hand movement and to draw attention to key aspects where technological improvements are emerging.

2. Literature Review

In such reviews, outlines of quantitative evaluation techniques used on a group of people with upper-limb issues are provided. The main points below include a historical summary of the most popular investigations and inquiries made by different researchers.

In 2012, Ninja P Oess et al developed an inexpensive instrumented gloves as shown in figure (1) that may be used to evaluate hand movement in clinical settings and rehabilitative settings. The signal drift of step responses from various sensor types was used to assess the stability of their output signals over time. A system was built that employed pre-measured curves to convert sensor output voltages into angles. Each sensory signal conditioning circuit's voltage supply was also elevated to improve sensor resolution. The intraclass correlation coefficient (ICC) was used to assess the repeatability of finger bending trajectories recorded while performing three everyday tasks. Four individuals with aberrant damage to the cervical spinal cord (cSCI) that affects hand function were evaluated to see if the glove could be used in everyday situations **[7]**.

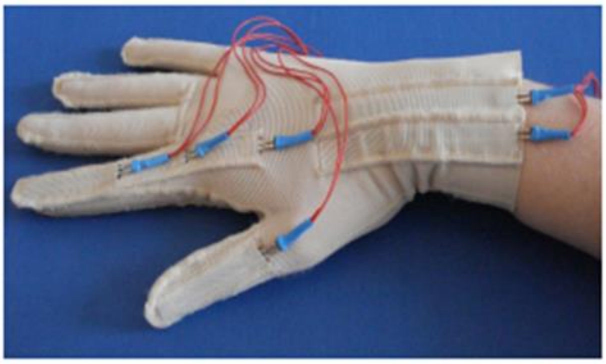

Fig.1 NeuroAssess Glove **[7]**.

In 2013, Shramana Ghosh created a low-cost glove-based system as shown in figure (2) that uses inertial sensors and IR markers to monitor the joint angles of the fingers, accelerations and velocities in both axes, as well as the positions and orientations of the fingertips. This data is then utilized to create a mechanical coupling using a unique approach developed by Robson et al **[9]**. This approach makes use of second-order kinematic task requirements that are connected to the curve of the objects being held and handled. The planar or spatial kinematic chains or fingers are then synthesized so that they do not break the normal direction and curvature limitations imposed by finger contact with an object. Finally, this is utilized to define and solve the chain/finger synthesis equations. The setup for the experiment consisted of a low cost glove based system for optical motion capturing with cameras that employ infrared emitters and reflective markers. Using accelerometer breakout boards, the fingers' acceleration was monitored. A healthy young adult is being used in preliminary tests to evaluate the present prototype gadget. His right hand was placed inside the prototype that was being examined and positioned on top of the patient as he sat at a table. The subject repeatedly engaged in a mild grasping exercise during the experiment **[10]**.

Fig.2 Prototype Glove-based Device **[10]** (A) Without Markers (B) with Markers.

In 2014, Henk G Kortier et al assessed hand kinematics to evaluate hand function. The finger and thumb joints have been suggested for 3D reconstruction. To build a precise 3D model of the hand for use with prostheses and other medical devices, inertial sensors were mounted to the hand, fingers, and thumb as figure (3). Inertial and Magnetic Measurement Systems (IMMS) have been shown to be accurate in determining body segment directions without the need of external actuators or cameras **[11]**. Because of the availability of Micro Electrical Mechanical Systems (MEMS) technology, compact and low-cost IMMS devices that can be easily integrated into textile clothing without compromising freedom of movement or tactile feeling have been developed. This experiment included five healthy male participants ranging in age from 21 to 53 years old with no known hand diseases. All tests were carried out using the subject's left hand, and according to the size of the hand, a small or large instrumentation set was attached. The length of the flexible printed circuit board (PCB) framework is the only variation between a small and large instrumentation set. Subjects during the first test put their flattened hand on a table top within a defined space. The patient was then instructed to lift his hand, flex all finger as well as thumb joints, hold this posture for 6 seconds, and then return to the flat initial position over 6 seconds. This cycle of flexion/flat was done ten times. The second test consisted of a clinched-fist posture with a plaster cast. This cycle of clenching was done ten times. During the clinch phase, subjects were free to keep their hands in either orientation. The range and standard deviation (SD) of all joint angles across all participants and trials during the flat phase (test 1) and during the clench phase (test 2) reflect the reproducibility of both tests **[12]**.

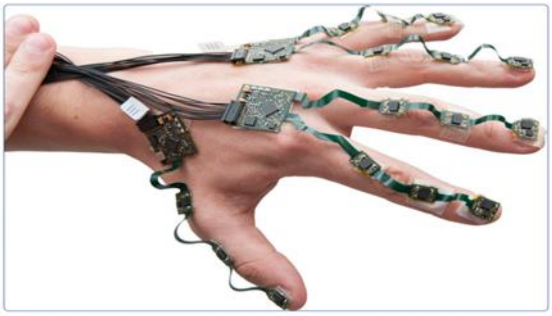

Fig.3 Glove hardware consisting of multiple printed circuit board strings which are attached to each finger segment **[12]**.

In 2014, Osama Nisar et al illustrated key factors that may be used to improve the effectiveness of a low-cost wearable glove interaction that measures a person's hand motions. The accelerometer that was used to sense the direction of the palm was included in the system. The flexing of fingers was measured using flex-bend sensors. These sensors are known as "flex bend sensors" because they monitor the bending of flexor tendons, like fingers. These sensors are often put on a wearable glove, one for each finger **[13]**. The sensor information is processed by an 8-bit microprocessor **[14]**. as shown in figure (4).

Fig.4 Wearable Glove Interface **[14]**.

In 2017, Kai Liu et al constructed a wearable finger state sensor system. When the system is in use, a sensor is fastened to the fingers to track movement, posture, pressure, and temperature data that is helpful for evaluating rehabilitation. A gyroscope-based circuit for sensing angular motion is constructed to complete the parameter testing of joint angular motion. A wearable system based on embedded software was developed to acquire data on the pressure, temperature, and orientation of the finger parts. This system successfully transmits messages to a terminal via Bluetooth. The system used C programming as its primary language. The second phase in the system's starting procedure was the hardware initialization mechanism, which sets register values for the Multiple Control Units (MCU) system clock, I2C bus, Analog to Digital Converter (ADC), and gyroscope hardware resources. The Bluetooth protocol stack is then started, which includes adding the Generic Access Profile (GAP), Generic ATTribute Profile (GATT), service, and characteristics **[15]**.

In 2017, Michael J Schreck et al Evaluated if an animation glove can be employed to offer a valid and reproducible evaluation of dynamic hand function and how this assessment changes when hand pathology is present. Ten subjects with no known hand pathology as well as 11 subjects with recognized stenosing tenosynovitis were evaluated on tasks involving functional ability at varying speeds, such as forceful and gradual fist formation and the fast and slow handle of a baseball, using an animation glove to capture range of motion and velocity (CyberGlove II) as shown in figure (5) **[16]**.

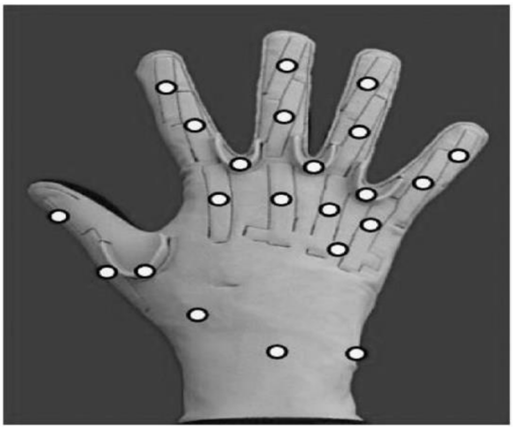

Fig.5 Sensor arrangement on the CyberGlove II **[16]**.

In 2018, Bor-Shing Lin et al proposed a modular data glove device for accurately and dependably recording kinematics of the hand as shown in figure (6). This data glove system's versatility is increased by its modular design. It gave medical professionals joint angles, joint accelerations, and angular velocities to modify rehabilitation treatment. For the purpose of recording hand motions during physical therapy, a data glove system was created. The gadget was developed using five flexible finger units (FFUs), a motion-capture board (MCB), finger flexible composite (FFC), a host system and an arm board are all part of the system. To test the data glove and complete a survey to ensure that it is wearable, 15 healthy individuals and 15 stroke victims were selected **[17]**.

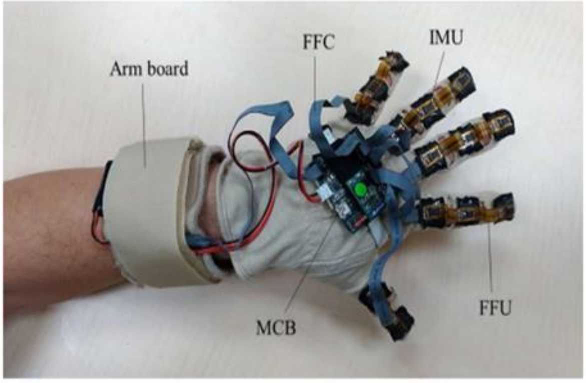

Fig.6 Modular design of the data glove **[17]**.

In 2018, Leonardo Cappello et al demonstrated that a fabric-based robotic glove that is portable, bidirectional (assisting both hand opening and closing), or multi-posture (enabling palmar grip and pinch grasp) is a feasible assistive option for individuals with limited hand strength and dexterity. The soft robotic glove is made to exert just the right amount of force to open and shut each finger, allowing for the grasping and lifting of small objects. The glove can grab objects of various forms because of its inherently flexible construction. It has been shown that this glove can compel a healthy user to grab an item with a force of 15 N, which is equivalent to an average of around 30% of an adult's maximal pinch force **[18]**. Researchers conducted a clinical motor function test on untrained volunteers with limited hand motor function due to spinal cord injury (SCI) with and without the aid of a soft robotic glove to investigate the effectiveness of the assistive glove. In ADL tasks, the soft robotic glove enhanced item handling. The variation in mean ratings between treatments was statistically significant for all subjects and modified items. **[19]**. fabric-based soft robotic glove shown in figure (7)

Fig.7 Soft robotic glove **[19]**.

In 2019, Angel Cardenas et al constructed a wearable device for purpose detection and evaluation of quality to help people with rehabilitation for extremities motion. To reduce the IMU sensors number, the researchers created a glove-based technique in which the inertial measurement unit (IMU) sensors collaborate with flexible sensors. The system's classification skills were enhanced by using a fuzzy logic assessment of the data approach. The sensors number required for aim detection was carefully evaluated while developing the system, and the fewer sensors included, the less likely it appeared that the system would interact with the patient's normal dexterous motions **[20]**. Furthermore, fewer sensors use less material overall, resulting in a more ecologically responsible project design as shown in figure (8).

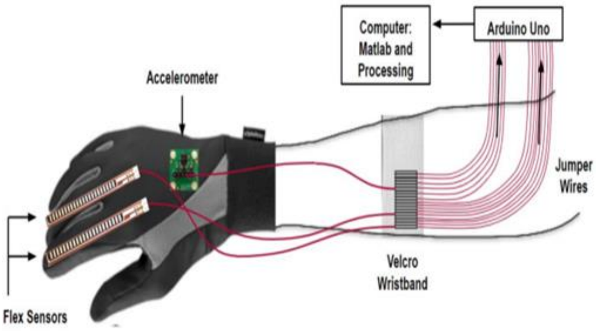

Fig.8 Hardware Components in Wearable Glove Assembly **[20]**.

In 2019, Christina Salchow-Hömmen et al devised a hand neuroprosthesis with an integrated hand sensor system as a component of a feedback-controlled device for patients with hand impairments. Approximately five sensor strips containing three IMUs each made up the system, which also included a base unit on the back of the hand and a wireless IMU on the forearm as shown in figure (9). Through the use of sensor fusion, inertial sensors may be utilized to detect the direction of body parts inside a global coordinate frame **[21]**. Two different settings are used to perform the experiments. First, tests with one person (#1) were carried out in a perfect laboratory environment free of magnetic disruptions. In order to conduct a more realistic evaluation, a second setting was investigated, which included trials consisting of functioning hand positions and movements in magnetic field-disturbed settings for all four participants (#1–#4) **[22]**.

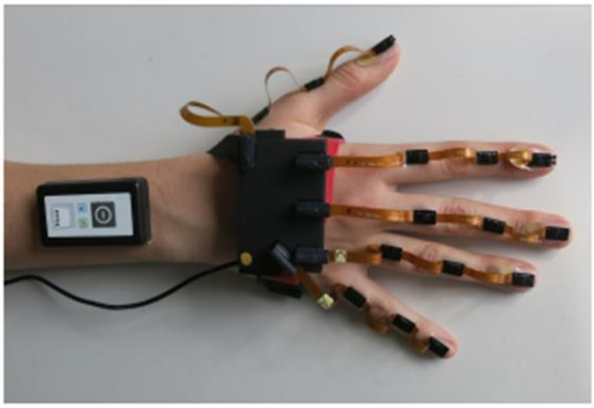

Fig.9 Modular hand sensor device based on IMU **[22]**.

In 2020, Jun Sik Kim et al created a wearable hand system with Real-Time algorithms for very precise assessment of finger joint angles in various hand sizes. The gadget used Five-fiber Bragg grating (FBG) strain sensors as well as techniques are used to obtain great accuracy even though the sensors are worn by people with various hand sizes as shown in figure (10). An FBG sensor ought to be able to monitor both the axial strain and the bending strain in order to estimate the angles of a finger joint. To more accurately quantify the bending strain, FBG strain sensors are therefore incorporated into a polymer matrix **[23,24]**. The offset length between an FBG strain sensor and the neutral bending axis increases the strain transferred to the FBG nodes when the sensor is bent. Four approaches were proposed for accurate, real-time computations: point strain (PTS), area summation (AREA), proportional summation (PS), and point strain/interference (PS/I or PS/I_α) **[25]**.

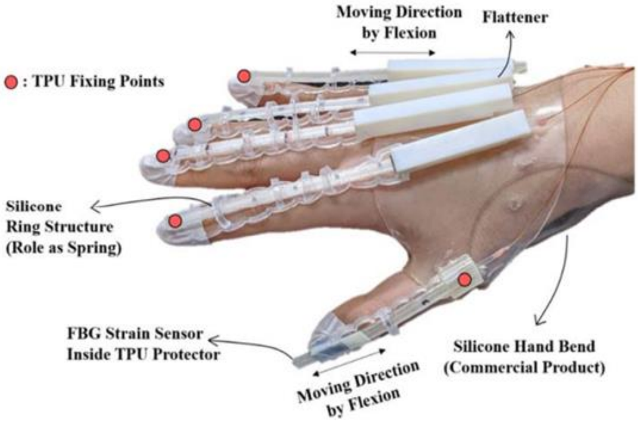

Fig.10 Wearable hand module and its components **[25]**.

In 2020, Jovana Malešević et al provided a hand functions evaluation process (BEAGLE) for kinematic monitoring of fingers and hand motions, with the intention of utilizing it as a technology-mediated rehabilitation tool. The technology, which incorporates inertial sensors incorporated into finger tips with a hand strap, is designed to be put on a disabled hand (spastic or flaccid) fast and simply as shown in figure (11). A range of motion estimate approach was used to show an unbiased evaluation of hand actions. To evaluate the effectiveness as well as the BEAGLE system's viability, a clinical trial including ten stroke patients in the acute period was done **[26]**.

Fig.11 BEAGLE system on a hand **[26]**.

In 2020, Stepan Lemak et al developed an inertial sensor-based finger motion detection solution. This research looked into finger tracking and compared the Madgwick filter extension to a basic switch (motion recognition) approach as shown in figure (12). In order to follow a single phalange in the flexion axis for varied movements, two approaches were used. A mode separation criterion was identified after an examination of their accuracy. By switching between several placement modes, these approaches were merged into a hybrid algorithm **[27]**.

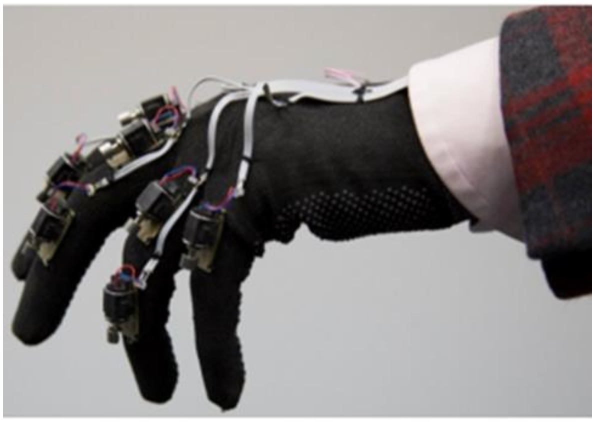

Fig.12 Hand tracking system using vibro-tactile output **[27]**.

In 2021, Diogo Schwerz de Lucena, et al created the HAND algorithm, a unique counting hand movements method within the Manumeter (Hand Activity Determined Using Nonlinear Detection) as shown in figure (13). The HAND algorithm's development has two basic objectives. First, it was hoped that the movement counts would be comparable to pedometer steps, where each step is a clearly defined and simple occurrence. Second, the method should not require user-specific calibration and should be particularly unaffected by hand size. These two qualities were desired for designing a useful tool that could deliver instantaneous, logical, quantitative feedback in addition to being able to quantify hand use. The manometer is made of a 6 degrees of freedom (DoF) inertial measurement unit (IMU), which has a gyroscope with a range of 500 degrees per second and an accelerometer with a 4 G range, each with both a 16-bit resolution as well as four magnetometers spaced 25 and 42 mm apart at the sides of a board encased in a rectangular watch like device. A real-time clock controls the time and date (PFC2123). The data from the IMU and magnetometers is gathered and stored on a 4 GB memory chip on-board at 52.6 Hz utilizing a structure (NRF52, Nordic Semiconductor) with only an ARM Cortex M4 CPU and wireless controllers. The data may then be sent to an additional board that has an SD card and utilizes the Improved Shockburst wireless protocol **[28]**.

Fig.13 The Manumeter consists of a ring with a permanent magnet and a sensing wrist. **[28]**.

The table (1) summarized the literature review.

Table1 Lists and characteristics of the paper summarized.

Year	Sensing Technology	System Design	Data	Filtering	Weight	Data Specimens	Evaluation

2012	Resistive bend sensors	NeuroAssess Glove	Kinematic	-	Light	(n = 10) healthy adults; (n = 4) cervical spine cord injury	Capacity
2013	Infrared (IR) markers and Accelerometer breakout boards.	Sensor Equipped Glove	Kinematic	Kalman filter	Heavy	Healthy young adults	Multiple tests
2014	Inertial and magnetic sensors	The system mounted on the hand using double sided adhesive tape	Kinematic	Kalman filter	Light	Healthy male volunteers (n=5) ranging in age from 21 to 53	Experiments
2014	Flex-bend sensors and accelerometer	Wearable Glove	Kinematic	Median filter	Light	collect 50 samples, discard the top and bottom five.	Performance
2017	Gyroscope and embedded system that assess skin temperature and pressure	Wearable device based on embedded system	Kinetic and Kinematic	-	Light	Hand dysfunction patients.	Experiments
2017	bend sensors	CyberGlove	Kinematic	-	Heavy	Stenosing tenosynovitis (n = 11); healthy participants (n = 10).	Capacity
2018	16 IMU sensors	Modular data glove	Kinematic	Mahoney filter	Heavy	Healthy subjects (n = 15); Stroke patients (n=15)	Questionnaire
2018	soft robotic actuators	Fabric-based robotic glove	Kinematic	-	Light	9 individuals with C4-C7 spinal cord injury.	Experiments

2019	IMU sensors with flexible sensors	Glove-based system	Kinematic	-	Light	25 different subjects	Multiple tests
2019	Five sensor strips with three IMUs	Modular hand sensor system	Kinematic	Kalman filters	Heavy	First trials with one participant (n=1), second trails with (n=1 to 4) participant	Experiments
2020	five fiber Bragg grating (FBG) strain sensors	Wearable hand module	Kinematic	Kalman filter	Light	four suggested algorithms: point strain, area summation, proportional summation	Quantitative
2020	Inertial sensors	BEAGLE system	Kinematic	Kalman filter	Light	Stroke survivors (n=10)	User interaction techniques
2020	Inertial sensors	Hand tracking device	Kinematic	Madgwick filter	Heavy	Make use of the three-link finger model.	Numerical experiment
2021	6 degrees of freedom (DoF) IMU	HAND algorithm Manumeter	Kinematic	Low-pass filter	Light	Participants with a stroke	Clinical Evaluations

3. The Discussions of Previous Studies

The glove's reliability was assessed by Ninja P. Oess et al who found that it provided ICC values ranging from 0.84 to 0.92, with a precision error of around ±5°. During testing for feasibility, it was demonstrated the glove's sensitivity enough to differentiate between various degrees among people with Cervical Spinal Cord Injury (cSCI) impaired hand function. Figure (14) (a), (b), and (c) show the finger bending trajectories that were captured by researchers from the 10 healthy volunteers and processed for tasks 1 through 3. Each task's unique pattern may be seen in the trajectories. Similar patterns may be seen in the different participants' curves.

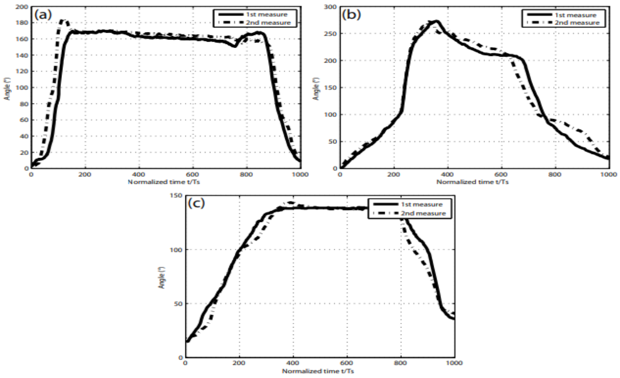

Fig.14 Evaluation of glove dependability. Four finger joint bending trajectories (Thumb interphalangeal (IP) and index metacarpophalangeal (MCP), proximal interphalangeal PIP, distal interphalangeal DIP joints).

For the purpose of capturing hand motion, an early reduced marker method was presented by Shramana Ghosh. Researcher was demonstrated how to rebuild the entire hand configuration using the decreased marker sets for motion capture by using an inverse kinematics method where this method based on the architecture of the finger linkages. The estimated joint angle for a grasping movement has Root mean square deviation (RMSE) of 2.

Henk G Kortier et al showed that magnetic and inertial sensors offer advantages in terms of static precision, dynamic range, and repeatability for ambulatory investigation of human hand and finger kinematics. This research makes multidegree-of-freedom joint motion estimation possible for low-cost sensors.

Osama Nisar et al was demonstrated that the median filter, which they utilized, generated the best results and continuously processed data, unlike the moving average filter, which was determined to be useless. The moving average filter did not remove the significant jumps that were seen in the samples, and these jumps were reflected in the average, so it is acting on moving data. As shown in figure (15) the results were carried out in two cases.

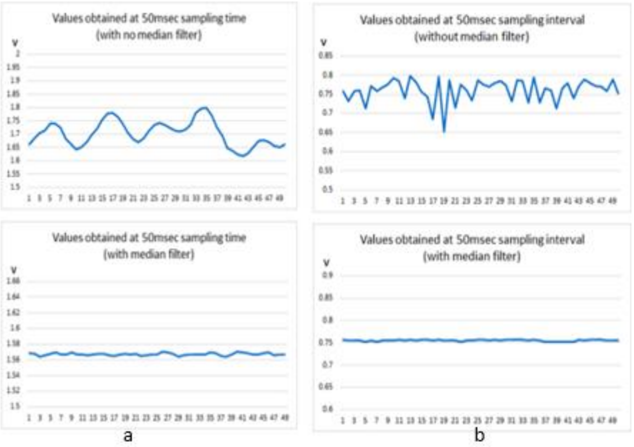

Fig.15 Graphical Results for: a) Case Test 1, b) Case Test 2.

Kai Liu et al showed that the experiments indicate that the system is stable and trustworthy, and that it can effectively gather the information for assessing the hand function as shown in figure (16).

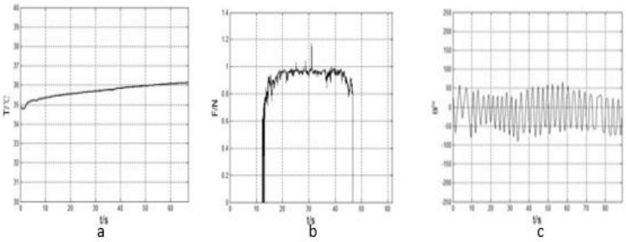

Fig.16 The Result of a) Temperature test b) Skin pressure test c) Joint angular motion test.

Michael J Schreck et al illustrated that the maximum extension and bending velocity of the middle and index fingers was greatest in the metacarpophalangeal but lowest in the distal interphalangeal in normal participants; however, the opposite was true for the ring finger. During evaluation, the animation glove was capable of recognizing a triggering event in participants with stenosing tenosynovitis. Furthermore, when the damaged hand was compared to the unaffected hand, there was a substantial reduction in the maximum velocity of the proximal interphalangeal joint in both flexion and extension with the slow grip task

The findings of Bor-Shing Lin et al demonstrated the dataglove was very well received by the participants. Additionally, a comparison of the recommended data glove with pertinent research showed that it performs better than other data glove systems.

Leonardo Cappello et al showed that an increase of 33.42 + 15.43% compared to the maximum test score demonstrates that the glove improves functional ability during ADL activities sufficiently. Furthermore, when employing the assisted soft robotic glove, lift force increased, confirming the device's usefulness in helping the hand function. The findings of their study confirm a fabric-based soft robotic glove as a viable device for assisting hand function in people who have experienced upper limb paralysis as a consequence of a spinal cord injury

The findings of the study of Angel Cardenas et al and testing were promising in terms of hand activity identification.

Christina Salchow-Hömmen et al showed that the obtained accuracy (around 1 cm RMSE) is enough for the neuroprosthesis' feedback regulation. The researchers used the suggested hand sensor method specifically to locate the best stimulation locations in electrode arrays.

Jun Sik Kim et al demonstrated the best algorithms PS and PS/I_ α were used for index-little fingers. PS/I_ α and AREA were the most effective algorithms for the thumb. The wearable hand module's mean absolute error (MAE) was measured to be 1.63 ± 1.97, and the average error angle was found to be 0.47 ± 2.51.

Jovana Malešević et al concluded that BEAGLE might be included in the recovery process in a therapeutic setting, according to the indicated usability criteria. A clinical trial with ten stroke patients in the subacute phase was conducted to assess the effectiveness and practicality of the BEAGLE system. The participants were treated in two successive intensity-matched rehabilitation cycles. The first was traditional therapy, whereas the second was a combination of traditional therapy and sophisticated functional electrical stimulation. Both before and after every step, assessments were carried out. All observed measures indicated statistically significant improvements from the start to the end of the second cycle, but in the first cycle of therapy, neither of these metrics shown a considerable improvement.

Stepan Lemak, et al found that the mathematical experiment demonstrates that this strategy is viable and solves several of the most significant constraints of tracking of inertial motion.

Diogo Schwerz de Lucena et al applied their proposed system on 29 patients with stroke that hand counting recorded at home did not rise till the subjects' scores on the test approached 50 percent normal. These findings demonstrate that a magnetometry technique based on threshold may measure hand motions without calibration while also validating the crucial idea of real-world hand function after stroke.

Conclusions

Over the past ten years, a number of research projects have developed technologies intended to measure shoulder, arm, and forearm gross motor motions. Relevant difficulties pertaining to the evaluation of hand function have received less attention. The aim of this review paper is to make a comprehensive study of the most important techniques that were used by researchers to evaluate and analyze hand movement. This review article also includes a statement of their results and the conclusions they reached, in order to allow the rest of the researchers to develop what they have reached in the coming years. Based on previous studies in recent years, this research paper concluded that assessment of hand kinematics is important for medical applications, hand function evaluation and characterization of healthful patterns of hand movement during ADL. On the other side, assessment of hand kinematics is essential in evaluating the influence of design on grip and developing anthropomorphic systems. This database can also be beneficial for prosthetic control and machine learning applications.

References

[1] Yu, H. L., Chase, R. A., Robert, A., & Strauch, B. (2004). Atlas of Hand Anatomy and Clinical Implications; Mosby: *St. Louis, MO, USA*

[2] Trybus, M., Lorkowski, J., Brongel, L., & Hladki, W. (2006). Causes and consequences of hand injuries. *The American journal of surgery*, 192(1), 52.

[3] Cooper, C. Fundamentals. Fundamentals of Hand Therapy; Elsevier: Amsterdam, The Netherlands, 2014; pp. 1–14.

[4] Yue, Z., Zhang, X., & Wang, J. (2017). Hand rehabilitation robotics on Poststroke motor recovery. *Behavioural neurology*.

[5] Richards, C., Mackenzie, N., Roberts, S., & Escorpizo, R. (2017). People with spinal cord injury in the United States. *American journal of physical medicine & rehabilitation*, 96(2), S124.

[6] Hawe, R. L., Scott, S. H., & Dukelow, S. P. (2019). Taking proportional out of stroke recovery. *Stroke*, 50(1), 204.

[7] Oess, N. P., Wanek, J., & Curt, A. (2012). Design and evaluation of a low-cost instrumented glove for hand function assessment. *Journal of neuroengineering and rehabilitation*, 9(1), 1.

[8] Dipietro, L., Sabatini, A. M., & Dario, P. (2008). A survey of glove-based systems and their applications. *IEEE transactions on systems, man, and cybernetics, part c (applications and reviews),* 38(4), 461.

[9] Robson, N., & Tolety, A. (2011, January). Geometric design of spherical serial chains with curvature constraints in the environment. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 54839,. 289).

[10] Ghosh, S. (2013). Capturing human hand kinematics for object grasping and manipulation (Doctoral dissertation).

[11] Roetenberg, D., Luinge, H. J., Baten, C. T., & Veltink, P. H. (2005). Compensation of magnetic disturbances improves inertial and magnetic sensing of human body segment orientation. *IEEE Transactions on neural systems and rehabilitation engineering*, 13(3), 395-
.

[12] Kortier, H. G., Sluiter, V. I., Roetenberg, D., & Veltink, P. H. (2014). Assessment of hand kinematics using inertial and magnetic sensors. *Journal of neuroengineering and rehabilitation*, 11(1), 1.

[13] AmbikaGujrati, K. S., & Khushboo, L. S. (2013). Mrs. Ambikapathy, "Hand-Talk Gloves with Flex Sensor: A Review". *International Journal of Engineering Science Invention*, 2(4), 43.

[14] Nisar, O., Imtiaz, M. A., Hussain, S., & Saleem, O. (2014). Performance optimization of a flex sensor based glove for hand gestures recognition and translation. *International Journal of Engineering Research & Technology*, 3(5), 1565.

[15] Liu, K., Mu, C., Wang, C., & Cheng, Y. (2018, February). Design of wearable system for hand function monitoring. *In 2017 3rd International Forum on Energy, Environment Science and Materials (IFEESM 2017) (. 619).* Atlantis Press.

[16] Schreck, M. J., Kelly, M., Lander, S., Kaushik, A., Smith, H., Bell, S., ... & Elfar, J. C. (2018). Dynamic functional assessment of hand motion using an animation glove: The effect of stenosing tenosynovitis. Hand, 13(6), 695.

[17] Lin, B. S., Lee, I., Chiang, P. Y., Huang, S. Y., & Peng, C. W. (2019). A modular data glove system for finger and hand motion capture based on inertial sensors. *Journal of medical and biological engineering,* 39(4), 532-
.

[18] Nilsen, T., Hermann, M., Eriksen, C. S., Dagfinrud, H., Mowinckel, P., & Kjeken, I. (2012). Grip force and pinch grip in an adult population: reference values and factors associated with grip force. *Scandinavian journal of occupational therapy*, 19(3), 288.

[19] Cappello, L., Meyer, J. T., Galloway, K. C., Peisner, J. D., Granberry, R., Wagner, D. A., ... & Walsh, C. J. (2018). Assisting hand function after spinal cord injury with a fabric-based soft robotic glove. *Journal of neuroengineering and rehabilitation*, 15(1), 1.

[20] Cardenas, A., Messersmith, R., & Newcomb, W. (2019). Assessment of Hand Gestures Using Wearable Sensors and Fuzzy Logic.

[21] Seel, T., & Ruppin, S. (2017). Eliminating the effect of magnetic disturbances on the inclination estimates of inertial sensors. *IFAC-PapersOnLine*, 50(1), 8798.

[22] Salchow-Hömmen, C., Callies, L., Laidig, D., Valtin, M., Schauer, T., & Seel, T. (2019). A tangible solution for hand motion tracking in clinical applications. *Sensors*, 19(1), 208.

[23] He, Y., Zhang, X., Zhu, L., Sun, G., Lou, X., & Dong, M. (2019). Optical fiber sensor performance evaluation in soft polyimide film with different thickness ratios. *Sensors*, 19(4), 790.

[24] Ge, J., James, A. E., Xu, L., Chen, Y., Kwok, K. W., & Fok, M. P. (2016). Bidirectional soft silicone curvature sensor based on off-centered embedded fiber Bragg grating. *IEEE photonics technology letters*, 28(20), 2237.

[25] Kim, J. S., Kim, B. K., Jang, M., Kang, K., Kim, D. E., Ju, B. K., & Kim, J. (2020). Wearable hand module and real-time tracking algorithms for measuring finger joint angles of different hand sizes with high accuracy using FBG strain sensor. *Sensors*, 20(7), 1921.

[26] Malešević, J., Kostić, M., Kojić, V., Đorđević, O., Konstantinović, L., Keller, T., & Štrbac, M. (2021). BEAGLE—A Kinematic Sensory System for Objective Hand Function Assessment in Technology-Mediated Rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 29, 1817.

[27] Lemak, S., Chertopolokhov, V., Uvarov, I., Kruchinina, A., Belousova, M., Borodkin, L., & Mironenko, M. (2020). Inertial sensor based solution for finger motion tracking. *Computers*, 9(2), 40.

[28] Schwerz de Lucena, D., Rowe, J., Chan, V., & Reinkensmeyer, D. J. (2021). Magnetically counting hand movements: validation of a calibration-free algorithm and application to testing the threshold hypothesis of real-world hand use after stroke. *Sensors*, 21(4), 1502.