Review Article

Ergonomic Evaluation of Biomechanical Hand Function

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1. Introduction

The human hand is a complex structure that performs various functions for activities of daily living and occupations. This paper presents a literature review on the methodologies used to evaluate hand functions from a biomechanics standpoint, including anthropometry, kinematics, kinetics, and electromyography (EMG). Anthropometry describes the dimensions and measurements of the hand. Kinematics includes hand movements and the range of motion of finger joints. Kinetics includes hand models for tendon and joint force analysis. EMG is used on hand muscles associated with hand functions and with signal-processing technology.

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application of biomechanical principles is important for preventing MSDs in order to improve working conditions and performance. In ergonomics, safety, and health, the hand is mainly evaluated to reduce the risk of MSDs. In product development, the hand is actively studied for the design of hand tools and cell phones. In rehabilitation, the hand is studied to evaluate the difference between patients and healthy individuals. Studying the hand is important for the development of hand-related simulations and robots in the digital manufacturing simulation and intelligence robot fields.

Detailed information on the technologies and methodologies used for hand analysis is required for nonexperts in the field of biomechanics such as hand-tool designers and safety supervisors to understand and choose easy and suitable methods. Hand anthropometry is simply the basis of biomechanical analysis. The range of motion (ROM) is the most commonly used functional measurement variable. Anatomical measurements and the ROM are usually used to design hand products and rehabilitation. The three-dimensional (3D) motion analysis system is currently the most commonly used technique to measure kinematic variables such as the trajectory, angle, velocity, and acceleration. This system needs marker sets and kinematic models for analysis. Several kinds of marker sets and kinematic models have been developed based on the purposes of different studies, and the accuracy of the system has been improved. Thus, it can provide important information for researchers to choose a suitable method. Kinetic hand models have been developed for analyzing the internal load (force and moment) of tendons and muscles during static and dynamic motions. These kinetic hand models have advantages and disadvantages with regard to the measurement method and complexity. Information from kinetic hand models can help a researcher design an experiment design. EMG is most commonly used in various research fields to evaluate the muscle activity, fatigue, and conduction velocity. For accurate analysis, understanding the use of the EMG equipment, electrode placement, muscle position, and signal-processing methods is important.

This paper presents a literature review of some technologies and methodologies used for hand-function analysis based on a biomechanical approach and the results of previous studies related to hand functions. The following four categories of hand-function analysis are covered: (1) anthropometry, (2) kinematics, (3) kinetics, and (4) EMG.

2. Methods

For this review, a systematic search was conducted using PubMed, Elsevier Science, and ScienceDirect databases, and Google Scholar on studies published from 1960 to 2014. The search was restricted to papers published in English and containing the terms “hand biomechanics,” “hand function,” “hand anthropometry,” “hand kinematic,” “hand kinetic,” “EMG of hand,” “finger joint angle,” “finger tendon force,” or “biomechanical hand model” in the title, abstract, or keywords. The initial search of the database yielded about 450 results. After a review of the titles and abstracts to reject duplicated articles, 245 articles were selected. After applying inclusion and exclusion criteria, 19 articles related to hand anthropology were selected, and 31 articles related to hand kinematics were identified from the manual targeted search. Eighteen articles or books related to hand kinetics, 10 articles related to hand EMG, and 26 articles related to hand anatomy, MSDs, posture, and functions were selected. In total, 104 articles were selected for inclusion in the current review (including 6 books and 6 reports). In the following sections, the term “reviewed articles” refers to the 104 selected articles.

3. Hand Anthropometry

3.1. Technology for hand anthropometry evaluation

Hand anthropometry is important to the design of products for human hands. Examples include machine guards, hand tools, and luggage handles. Hand anthropometric parameters are categorized into anatomical measurement variables such as the length, width, and circumference [16–18]; functional measurement variables such as the handgrip span, flexion and extension ROMs of the fingers and wrist, and abduction/adduction and deviation ROMs of the wrist in engineering anthropometry [16,18–20].

Hand anthropometry can be directly measured using digital calipers, circumference tapes, and finger circumference gauges [16,21] and can also be measured from photographs [18,22] and scans [23,24]. Goniometers and 3D motion analysis systems are used to measure the width, flexion, and extension ROMs [23]. Direct measurement is easy and efficient, but skin movement and experimenter error can occur. Photography measurement requires less time than direct measurement, and the recorded information can be repeatedly used [26], but measuring the circumference is difficult. Although 3D scans can be used to measure diverse hand areas precisely, data can be distorted due to movements during the scan.

3.2. Anatomical measurement variables

In general, anthropometry for anatomical measurement variables is divided into general and application surveys. General surveys are used to explain the hand variation of large populations. Their main purpose is to describe populations. By contrast, application surveys are used to gather data for a specific product. Therefore, an application survey often uses few individuals but with strictly defined populations such as occupational groups [18]. Following the trend of general surveys for hand anthropometry, Vicinus [27] measured 44 dimensions of both hands in 253 males. The results for the left and right hands were significantly different. The left hand had a larger breadth than the right hand, whereas the right hand had a larger length than the left hand. Moreover, the correlation between the hand length and breadth dimensions was generally poor. Garrett [28,29] conducted a comprehensive general survey on 148 males and 211 females to measure 34 dimensions of the hand and 17 dimensions of engineering anthropometry [16]. This study showed a wider range of hand dimensions than previous studies. Gooderson et al [30] measured 62 dimensions of the left and right hands in 300 males and 187 females in the British army. Similar to Vicinus [27], they found a low correlation between the hand length and breadth dimensions. Greiner [18] measured 64 hand dimensions. Recently, Okunribido [31] measured 18 dimensions of the hand in 37 females from Ibadan and western Nigeria and compared them with those of other populations. The results showed that hand dimensions differed between populations. Similarly, Mandahawi et al [32] measured 24 hand dimensions in 115 males and 120 females and analyzed the difference between sexes and between Jordanians and other populations. Their results showed significant differences with regard to the sex and population.

With regard to examples of application surveys for hand anthropometry, Barter and Alexander [33] measured 18 hand dimensions in 100 individuals to develop a glove sizing system. In their study, hand dimensions were selected for developing the glove system, and these dimensions are not normally measured in most hand surveys. Rosenblad-Wallin [34] measured 33 hand dimensions for the development and design of army gloves.

Hand anthropology data are used to design ergonomic tools or equipment and space. Thus, the measurement criteria and
dimensions of hand anthropometry differ according to the study purpose, such as general and application surveys. Although the hand dimensions measured in application surveys were focused on specific user groups, they were part of those considered in general surveys. Table 1 presents the hand anthropometry dimensions for the previous studies summarized in this literature review. The dimensions in Table 1 represent the length, breadth, and circumference, which are commonly used as basic data in hand anthropometry.

4. Hand kinematics

4.1. Technology for hand kinematics

Numerous studies have evaluated the angle, velocity, trajectory, and acceleration during various hand functions. The following are common devices used for measuring various hand functions: X-rays, magnetic resonance imaging (MRI), manual goniometers, electrogoniometry, video technique, and marker-based motion analysis systems [35–41]. X-ray and MRI analyses are common methods for clinical observation. However, X-ray measurements carry the risk of radiation exposure [35]. The thumb trapeziometacarpal joint is difficult to measure with goniometry [42].

To compensate for these limitations, current research is actively studying the use of motion analysis systems for measuring hand functions. Motion analysis systems analyze the posture and movement continuously by calculating the 3D trajectories and have the benefit of obtaining more reliable data than other methods [41,43–45]. A motion analysis system requires reflective markers to adhere to hand joints for measurement: the angle, velocity, trajectory, and acceleration of each joint are then evaluated using a model based on a mathematical algorithm.

Four types of marker sets can be used for hand analysis. There are three skin-marker attachment methods. The “one marker per joint” attachment method attaches markers to each finger joint head [41,46–51]. The “two markers per segment” method attaches markers to the distal and proximal heads of the finger segments [52–55], and the “three markers per segment” method attaches markers with a triangular shape to finger segments [56,57]. The “one marker per joint” attachment method has been used to analyze static conditions such as power and pinch grips. The “two markers per segment” attachment method has been used to analyze dynamic movements such as a pinching motion or the ROM of finger joints. The “three markers per segment” attachment method has been used to analyze dynamic movements such as a gripping motion or the ROM of finger joints. The “cluster marker” attachment method has been used to measure the ROM of finger joints [58,59]. The “one marker per joint” attachment method has

Table 1
Summary of hand anthropometry dimensions

| No. | Variable                | Length  | No. | Variable                | Breadth/circumference |
|-----|-------------------------|---------|-----|-------------------------|-----------------------|
| 1   | D1 length               | 26      | 26  | D2 MCP link length      | 51                    |
| 2   | D2 length               | 27      | 27  | D3 MCP link length      | 52                    |
| 3   | D3 length               | 28      | 28  | D4 MCP link length      | 53                    |
| 4   | D4 length               | 29      | 29  | D5 MCP link length      | 54                    |
| 5   | D5 length               | 30      | 30  | D1 PIP link length      | 55                    |
| 6   | Crotch 1 height         | 31      | 31  | D1 DIP link length      | 56                    |
| 7   | Crotch 2 height         | 32      | 32  | D2 DIP link length      | 57                    |
| 8   | Crotch 3 height         | 33      | 33  | D2 MCP link length      | 58                    |
| 9   | Crotch 4 height         | 34      | 34  | D2 PIP link length      | 59                    |
| 10  | D1 height               | 35      | 35  | D3 MCP link length      | 60                    |
| 11  | D2 height               | 36      | 36  | D3 MCP link length      | 61                    |
| 12  | D3 height               | 37      | 37  | D3 PIP joint circumference | 62               |
| 13  | D4 height               | 38      | 38  | D4 DIP link length      | 63                    |
| 14  | D5 height               | 39      | 39  | D4 MCP link length      | 64                    |
| 15  | D1 tip to wrist crease length | 40  | 40  | D4 PIP link length      | 65                    |
| 16  | D2 tip to wrist crease length | 41  | 41  | D5 DIP link length      | 66                    |
| 17  | D3 tip to wrist crease length | 42  | 42  | D5 MCP link length      | 67                    |
| 18  | D4 tip to wrist crease length | 43  | 43  | D5 PIP link length      | 68                    |
| 19  | D5 tip to wrist crease length | 44  | 44  | Palm length             | 69                    |
| 20  | D1 link length          | 45      | 45  | Hand length             | 70                    |
| 21  | D2 link length          | 46      | 46  | Wrist-index grip length | 71                    |
| 22  | D3 link length          | 47      | 47  | Wrist-thumbtip length   |                        |
| 23  | D4 link length          | 48      | 48  | Forearm-hand length     |                        |
| 24  | D5 link length          | 49      | 49  | Hand length from digitizer |                  |
| 25  | D1 MCP link length      | 50      | 50  | Thumbtip reach          |                        |

Table 2
Marker attachment method and kinematic model of previous studies

| Model                 | Attachment method | Authors            |
|-----------------------|-------------------|--------------------|
| Cheng and Peary’s model | One marker        | Gupta et al [46],  |
|                       |                   | Carpinella et al [49], Baker et al [51], Bazanski [63] |
|                       | Two markers       | Ryu et al [52], Chiu et al [53], Sakai et al [54] |
| Eulerian angle model   | Three markers     | Buczek et al [56], Cerveri et al [57], Gehrmann et al [59] |
|                       | Cluster marker    |                    |

1. One marker per joint
2. Two markers per segment.
3. Three markers per segment.
been recommended for use in the clinical research field because it causes less discomfort to patients when they move their hand, and it is easy to use the same marker placement for each patient. The "two markers per segment", "three markers per segment", and "cluster marker" attachment methods have been recommended for use in the biomechanical field because they are less affected by skin movement.

The Eulerian angle model [25,53,60,61] and Cheng and Pearcy's model [62] are commonly used to analyze the angle, velocity, trajectory, and acceleration of a motion based on the measured markers. The Eulerian angle model is the most commonly used model for motion analysis and explains the orientation of a rigid body in space. An arbitrary direction in space is obtained by three rotations using Eulerian angles. From this, the finger joint flexion/extension, abduction/adduction, and supination/pronation are calculated. Thus, each model uses different mathematical algorithms. The velocity, trajectory, and acceleration are also calculated from this model. The Eulerian angle model can calculate the angle of 2D planes because a 3D axis cannot be defined with only one or two markers. By contrast, an Eulerian angle model with the three markers per segment and cluster marker attachment methods can be used to calculate the angles of all dimensional planes.

4.2. ROM of hand

The ROM of the hand is the most commonly used functional measurement variable. The ROM measurements include the flexion/extension, abduction/adduction, and pronation/supination of the CMC, MCP, and IP joints of the thumb, and MCP, PIP, and DIP joints of the other four fingers [25]. Finger motion measurements are divided into active ROM (AROM) and passive ROM (PROM) [64]. Similarly, Hume et al [65] classified their finger motion measurements as functional ROM (FROM) and normal ROM (NROM). FROM and NROM take the maximum and minimum angles in static positions, whereas AROM and FROM explain dynamic or functional

| Finger | Swanson [67] | Becker and Thaker [58] | Chao et al [25] | Hume et al [65] | Degeorges and Oberlin [69] | Yoshida et al [36] | Zheng and Li [70] | Mean (standard deviation) |
|--------|--------------|------------------------|-----------------|-----------------|---------------------------|------------------|------------------|------------------------|
| Thumb  | CMC —        | —                      | 52.9            | —               | 56                        | 77               | 45               | 61 (14)                |
|        | MCP —        | —                      | —               | —               | 77                        | 50               | 61 (14)          |
|        | IP —         | —                      | —               | —               | 81                        | 80               | 81 (1)           |
| Index  | MCP 62       | 71                     | 83              | 97              | 85                        | 80               | 85 (15)          |
|        | PIP —        | 104                    | 101             | 57              | 80                        | 80               | 80 (11)          |
|        | DIP —        | 61                     | 73              | 73              | 80                        | 80               | 80 (11)          |
| Middle | MCP 64       | 85                     | 90              | 100             | 85                        | —                | 85 (15)          |
|        | PIP —        | 104                    | 103             | 114             | —                         | —                | —                |
|        | DIP —        | 74                     | 80              | —               | 107                       | 107              | 107 (6)          |
| Ring   | MCP 67       | 85                     | 88              | 107             | —                         | —                | 87 (16)          |
|        | PIP —        | 107                    | 105             | 110             | —                         | —                | —                |
|        | DIP —        | 67                     | 75              | —               | 107                       | 107              | 107 (3)          |
| Little | MCP 64       | 86                     | 90              | 105             | —                         | —                | 86 (17)          |
|        | PIP —        | 99                     | 103             | 111             | —                         | —                | 104 (6)          |
|        | DIP —        | 71                     | 78              | —               | 58                        | —                | 69 (10)          |

Table 3 Range of motion of finger flexion.

Flexion angles are presented in degrees.

5. Hand kinetics

5.1. Technology for kinetics evaluation

Studies on hand kinetics have analyzed the force, moment, and torque of the fingers and tendons. These studies have used a tendion-force-measurement system [66], force transducers [71],
movements during grasping motions [82], and estimate the functions [25, 60, 78] of the extrinsic muscles of the hand have been measured directly by instrumenting the tendon forces from the extrinsic muscles of the digitorum superficialis; MCP, metacarpophalangeal joint; PIP, proximal interphalangeal joint.

The forces are presented in Newton.

DIP, distal interphalangeal joint; FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis; MCP, metacarpophalangeal joint; PIP, proximal interphalangeal joint.

There are two common methods for analyzing tendon forces, namely, (1) analytical models and (2) experimental direct tendon-force-measurement models. Analytical models are based on the equation of static equilibrium at each joint of the finger to evaluate the tendon forces based on an externally applied force. Analytical models have a problem when the system being analyzed is redundant (i.e., there are more muscles than strictly necessary to obtain equilibrium across a joint). To solve this problem, two methods have been used, namely, reduction [60, 85] and optimization [86]. The reduction method is used to reduce the number of excessive variables until the number of unknown forces is equal to

Table 5
Tendon and joint forces during various hand functions

| Hand function | Finger | Tendon force | Joint force | Authors |
|---------------|--------|--------------|-------------|---------|
|               | FDP    | FDS          | MCP         | PIP     | DIP     |
| Power grasp   | —      | 4.0–20.0     | 1.25–15.0   | —       | —       | Bright and Urbaniak [89] |
|               | —      | 4.0          | 0.60        | —       | —       | Schuind et al [88]      |
| Index         | 2.77   | 2.53         | 12.7        | 4.35    | 0.09    | Chao et al [60]         |
| Middle        | 3.05   | 4.23         | 3.90        | 7.11    | 0.17    | Schuind et al [88]      |
| Little        | 3.37   | 3.40         | 4.50        | 6.02    | 3.31    | Schuind et al [88]      |
| Middle        | 3.37   | 3.75         | 5.18        | 6.80    | 3.89    | Chao et al [25]         |
| Index         | 3.17–3.47 | 1.51–2.14   | 3.20–3.70   | 4.50–5.30 | 2.80–3.40 | An et al [78]         |
| Pinch grip    | index  | —            | —           | 5.50    | 4.60    | Berme et al [90]        |
| Tip pinch     | —      | 2.50–12.5    | 1.00–7.50   | —       | —       | Bright and Urbaniak [89] |
|               | —      | 8.30         | 1.90        | —       | —       | Schuind et al [88]      |
| Index         | —      | —            | 3.50–3.90   | 4.40–4.90 | 2.40–2.70 | An et al [78]         |
| Key pinch     | index  | —            | —           | 14.70–27.10 | 4.90–19.40 | 2.90–12.50 | An et al [78]         |
| Pulp pinch    | —      | —            | —           | 4.00–4.60 | 4.80–5.80 | 3.00–4.60 | An et al [78]         |

The forces are presented in Newton.

DIP, distal interphalangeal joint; FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis; MCP, metacarpophalangeal joint; PIP, proximal interphalangeal joint.

5.2. Kinetic hand model

DIP, distal interphalangeal joint; ED, extensor digitorum communis; EPB, extensor pollicis brevis; EPL, extensor pollicis longus; FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis; FPL, flexor pollicis longus; IP, interphalangeal joint; MCP, metacarpophalangeal joint; PIP, proximal interphalangeal joint.

Table 6
Hand muscles and the action, origin, insertion, and location of common extrinsic muscles of hand functions

| Muscle | Action | Origin | Insertion | Location |
|--------|--------|--------|-----------|----------|
| FDS    | Flexion of PIP and MCP joints | Common tendon from the medial epicondyle of the humerus, coronoid process of the ulna, and oblique line of the radius | All of these tendons are inserted in the volar surface of the 2nd phalanx | Point index finger to biceps tendon and insert needle electrode from the ulna to the tip of the index finger. The electrode travels through the palmaris longus |
| FDP    | Flexion of DIP joints | Upper three-fourths of volar and medial surfaces of the ulna and interosseous membrane | Volar surfaces of bases of distal phalanges of the 4 fingers | Place the tip of the little finger on the olecranon and the ring, middle, and index fingers along the shaft of the ulna |
| FPL    | Flexion of IP and MCP joints of the thumb | Medial epicondyle of the humerus | Palmar aponeurosis and flexor retinaculum | At the junction of the upper and middle third of a line joining the medial epicondyle and middle of the volar surface of the wrist |
| EPL    | Extension of IP and MCP joints | Ulna adjacent to the interosseous membrane | Dorsal base of the thumb Distal phalanx through the thumb extensor mechanism | On the dorsal side of the forearm |
| EPB    | Extension of MCP joint of the thumb | Radius adjacent to the interosseous membrane | Over tendons of radial extensors and brachioradialis to the base of the proximal phalanx of the thumb | On the dorsal side of the forearm |
| ED     | Extension of MCP joints | Common extensor tendon from the lateral epicondyle of the humerus | On the dorsal surface of the base of the second to 5th phalanges of the fingers | Grasp the forearm at the junction of the upper and middle third with the thumb and middle finger on the radius and ulna. With the index finger, bisect these 2 points and insert a needle electrode at the tip of the index finger to a depth of 1.27 cm |
| APL    | Abduction of the thumb | From dorsal surface of the body of the ulna, interosseous membrane, and middle third of the body of the radius | Lateral aspect of the base of the 1st metacarpal | Over the shaft of the radius at the mid forearm. The electrode travels through the ED |
the number of required equilibrium equations, thus eliminating static indeterminacy. In contrast to eliminating unknown muscle forces in the redundant system, the optimization method involves obtaining a unique solution from a mathematical formulation and optimization algorithm.

Experimental direct tendon-force-measurement models provide a more comprehensive understanding of the mechanism of the tendons inside the fingers. There are three common methods for experimental analysis, namely, (1) EMG, (2) in vivo, and (3) cadaveric. The EMG method is a readily available technique that can be applied to force and muscle-function analyses. For in vivo methods, many researchers have developed force transducers to directly measure the tendon force during various hand functions [75, 76, 87, 88]. In case of cadaver study, the mass, volume, and muscle fiber length are measured to estimate the tendon force during hand function from cadaver [76, 87]. Table 5 lists the tendon and joint forces in the flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), MCP, PIP, and DIP for various hand functions. Many researchers have attempted to gather accurate data on internal loads during various hand functions because they can be used to evaluate physical loads. The forces of the tendons and joints differ according to the hand functions and fingers. In general, the MCP joint of the index finger exhibits the largest joint force for various hand functions. However, previous studies have provided insufficiently accurate data for all finger joints.

6. Hand EMG

6.1. Hand muscles and technology of surface EMG

Surface EMG (sEMG) can be used to evaluate various biomechanical characteristics, including localized muscle activity, fatigue, and conduction velocity [91]. The musculoskeletal system conducts the motor unit active potential, which can be expressed as the firing rate in sarcolemma. The firing rate is the standard used for evaluating muscle activity based on the signal amplitude. EMG provides a physiological method for assessing muscle usage and the magnitude of muscular loading and is directly related to muscular effort [92]. Muscle activity during different occupational activities is often evaluated by EMG and presented in terms of the percentage of maximal activity [93]. Christensen [94] defined muscle fatigue as any reduction in the force-producing capacity of a muscle.

The muscles associated with hand functions can be divided into extrinsic and intrinsic muscle groups. Extrinsic muscles originate in the forearm and are among the largest hand muscles; thus, sEMG is often evaluated by EMG and presented in terms of the percentage of maximal activity [93]. Christensen [94] defined muscle fatigue as any reduction in the force-producing capacity of a muscle.

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The FDS, FDP, and flexor pollicis longus are the major muscles for the flexion and extension of four fingers. The extensor pollicis longus, extensor pollicis brevis, extensor digitorum communis, and abductor pollicis longus are the major muscles for the flexion, extension, and abduction of the thumb. These muscles are located in the forearm and are among the largest hand muscles; thus, sEMG is suitable for use.

6.2. Signal-processing technology for EMG evaluation

To evaluate the amplitude of an EMG signal, many signal-processing methods have been suggested, such as the mean absolute value, root mean square (RMS), envelope detection, and ensemble averaging [98]. During maximal voluntary contraction (MVC), several changes are observed. The integrated EMG or RMS shows a gradual decrease. The mean power frequency (MPF) shows a rapid shift to a lower frequency during sustained MVC [99].

Previous researchers have used EMG to study the mechanism of intrinsic and extrinsic finger muscles during specific hand positions and power grips. Armstrong et al [3] used rectified sEMG signals from the forearm flexor muscles to predict finger forces produced during tasks involving pinching, grasping, and pressing. Researchers have continued to examine the feasibility of predicting the grip force from EMG data with reasonably good results [100, 101].

7. Discussion

This paper presents a literature review of some technologies and methodologies used for hand-function analysis based on a biomechanical approach. Four approaches to hand-function analysis are presented, namely, (1) anthropometry, (2) kinematics, (3) kinetics, and (4) EMG. Anthropometry includes technology to evaluate hand-measurement variables. Kinematics includes technology to evaluate the ROM of each finger joint. Kinetics includes technology and various kinetic hand models for the analysis of tendon and joint forces. EMG includes hand muscles associated with hand functions, sEMG technology, and signal-processing technology.

In general, anatomical measurement variables are classified for use in general or application surveys based on the purpose of the study. A general survey measures a large number of hand dimensions of numerous individuals; its main purpose is to describe a population. By contrast, an application survey measures fewer hand dimensions because only variables that are closely related to the product of concern are selected and measured. Thus, the measured dimensions and number of individuals vary depending on the purpose. However, no sufficient studies were performed to standardize the optimal number of individuals and related dimensions. Therefore, a general survey of hand anthropometry is required to determine the optimal number of individuals that provides reliable statistic data. Application surveys of hand anthropometry should be used to develop standards for dimensions closely related to the product of concern.

In kinematics, hand-function analysis uses various marker sets and models to evaluate the angle, velocity, trajectory, and acceleration of the hand. Techniques for measuring various hand functions include X-rays, MRI, manual goniometers, electromyography, video techniques, and marker-based motion analysis systems. To analyze the angle, velocity, trajectory, and acceleration of a hand based on the measured marker, the Eulerian angle model and Cheng and Pearsay’s [62] model are commonly used. Finger motion measurements are roughly classified into AROM, PROM, NROM, and FROM. PROM and NROM measure the maximum and minimum angles in static positions, whereas AROM and FROM explain dynamic or functional movements such as gripping or pinching.
Studies on kinetics have analyzed the force, moment, and torque of fingers and tendons. These parameters can be measured either directly or indirectly. Equipment used for measurement includes tendon-force-measurement systems, novel force transducers, dynamometers, force gauges, and pinch gauges. Tendon forces from the extrinsic muscles of the hand are measured directly by instrumenting the tendon. Kinetic hand models can be divided into analytical and experimental direct tendon-force-measurement models. Analytical models are based on the equation of static equilibrium at each joint of the finger and such models evaluate the tendon force based on an externally applied force. Experimental direct tendon-force-measurement models provide a more comprehensive understanding of the mechanism of the tendons inside the fingers.

The muscles associated with hand functions can be divided into extrinsic and intrinsic muscle groups. Six extrinsic muscles are commonly monitored in hand-function analysis using sEMG. Table 6 lists the action, origin, insertion, and location of these muscles. Most studies have used signal-processing techniques such as zero crossing, RMS, average EMG amplitude, mean sEMG, MFP, and maximal voluntary electrical activity. Previous studies on muscle fatigue and characteristics based on the EMG signals have only considered static postures, not dynamic postures, and simply considered the relative muscle activity from the MVC. However, in the case of dynamic gripping tasks, the muscle fiber depth and length change with time, and the distance between the sEMG electrode and muscle fiber also changes. A muscle–tendon moment difference is generated with changes in the muscle contraction velocity, and rapid motor unit recruitment by contraction shows flexible signal characteristics. Therefore, using EMG on dynamic contractions requires a different interpretation from static contractions.

The biomechanical analysis of the hand is an interdisciplinary study of the mechanical movement and force of the hand’s musculoskeletal system; it includes hand anthropometry, kinematics, kinetics, and EMG. Biomechanical analysis aims to provide design guidelines for hand tools and devices or for a safe working environment. This review paper provides fundamental knowledge on the hand biomechanics in terms of anthropometry, kinematics, kinetics, and EMG.

8. Summary and conclusion

8.1. Hand anthropometry

Hand anthropometry data can be used to design hand-guard products (e.g., gloves), hand-controlled products (e.g., remote control, mouse), and hand-operated tools (e.g., screwdriver, hammer). Hand anthropometry can be directly measured using various equipment and devices. In recent times, 3D scans are commonly used for this purpose because they can measure diverse hand areas precisely and easily. Hand anthropometry dimensions are largely divided into length, breadth, and circumference under the static condition. In general, the length and breadth have 50 and 10 variables, respectively. The circumference has 10 variables (Table 1). When using hand anthropometry data, choosing the appropriate dimensions and number of populations and individuals for the purpose of the study is very important. Previous studies have failed to consider the breadth and circumference of the thumb as measurement dimensions. Thus, future research is required to measure the thumb dimensions.

8.2. Hand kinematics

For accurate evaluation of kinematic variables, various fields commonly use a 3D motion analysis system. This system can obtain 3D data more reliably compared with other methods. The kinematic hand model and marker attachment methods require 3D motion analysis to evaluate the kinematic variables. Many researchers have difficulties with selecting a marker attachment method to accurately measure hand functions. Based on this review, the “one marker per joint” method is recommended for greater patient comfort and easy marker placement, although any marker attachment method can be used under static conditions. The “three markers per segment” and “cluster marker” methods evaluate hand movements more accurately because of their robustness to skin movement. Thus, they are recommended for experiments conducted under dynamic conditions.

Table 3 lists the ROMs for finger flexion according to previous studies. The PIP joint (mean: 105°) has the largest flexion ROM followed by the MCP (mean: 84°) and DIP joints (mean: 69°). Table 4 lists the joint flexion angles for various hand functions. These previous studies focused mainly on the flexion angle of the four fingers excluding the thumb. However, the thumb is the most important part of the hand and has a wide range of activities during hand functions. Thus, future research will involve examining the ROM and hand functions of the thumb, and the various hand functions will be measured in 3D.

8.3. Hand kinetics

The technologies for kinetics evaluation can be roughly divided into direct and indirect measurements. In general, the external load is measured directly with instruments, and the internal load is predicted analytically through kinetic models. Many previous studies have focused on measuring the force, moment, and torque during hand functions. Evaluating the joint force, moment, and torque requires accurate anthropometry data such as the segment mass, center of mass, center of gravity, and radius of gyration. Thus, accurate anthropometry data of the hand will be considered to develop a hand kinetics model in future research.

8.4. Hand EMG

In EMG, the most important factors are choosing suitable muscles, accurate attachment of the electrodes, and choosing a suitable signal-processing method for the research purpose. Table 6 lists the most commonly used hand muscles in hand functions when researchers use EMG. Most studies have used signal-processing methods such as RMS and MFP. Previous studies on muscle fatigue and characteristics based on the EMG signals have only considered static postures, not dynamic hand functions. They simply considered the relative muscle activity from the MVC. However, in the case of dynamic hand functions, the muscle fiber depth and length change with time and distance, and therefore, changes occur between the sEMG electrode and muscle fiber. Moreover, a muscle–tendon moment difference is generated when the muscle contraction velocity changes, and rapid motor unit recruitment by contraction shows flexible signal characteristics. Therefore, the EMG signal of dynamic hand functions should be interpreted differently compared with that of static hand functions.

Conflicts of interest

All contributing authors declare no conflicts of interest.

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