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Assessing Assumptions in Kinematic Hand Models: A Review

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***Abstract*—The incredible complexity of the human hand makes accurate modeling difficult. When implementing a kinematic hand model, many simplifications are made, either to provide simpler analytical solutions, to ease implementation, or to speed up computation for real time applications. However, it is important to understand the trade-offs that certain simplifications entail – the kinematic structure chosen can have important implications for the final model accuracy. This paper provides a brief overview of the biomechanics of the human hand, followed by an in-depth review of kinematic models presented in the literature. This review discusses some simplifications that may often be inappropriate, such as assuming no metacarpal bone motion or assuming orthogonal, intersecting thumb axes. This discussion should help researchers select appropriate kinematic models for applications including anthropomorphic hand design, human-computer interaction, surgery, rehabilitation, and ergonomics. Some modeling issues remain unclear in the current literature. Future work could compare thumb MCP models and better investigate unactuated compliant degrees of freedom in the hand.**

I. Introduction

THE kinematic complexity of the human hand, with its complex bone and joint structure and more than twenty degrees of freedom, makes accurate modeling challenging. This complexity forces researchers to develop simplified models to make analyzing the hand more manageable. However, the assumptions made have important implications for the accuracy of the final model [1]. For example, in order to improve the accuracy of modeled thumb tip forces based on a simplified thumb model with orthogonal and intersecting axes at all joints [1], a more complex virtual five-link model was adopted that provided significantly better results [2]. As with any model, it is important for the researcher to understand its limitations to assure that the desired behaviors are produced and that the assumptions of the model are not violated.

This review focuses on the *kinematic* structure of the human hand and simplifying assumptions that are used in a wide range of models described in the literature. Other aspects of hand models such as muscle and tendon modeling, hand surface modeling, marker tracking, and gesture recognition are considered out of scope for this paper. While no review articles focusing on kinematic hand modeling were found, some related resources are available: [3] and [4] describe hand biomechanics; [5] discusses using hand models to study neuromuscular control; [6] and [7] review gesture and pose recognition techniques; and [8] gives short summaries of a wide variety of topics in hand modeling.

In this paper, we first describe the basic bone and joint structure of the hand, as well as methods for establishing joint axis locations. Next, kinematic models for different joints are discussed, along with the explicit and implicit assumptions commonly used in applying the models. Finally, general applications of the models are summarized, followed by some conclusions regarding effective hand model application.

II. Biomechanics of the Hand

In this section, a brief summary of hand biomechanics is provided, with emphasis on considerations related to bone structure (II.A) and establishing axes of motion (II.B).

A. Bone Structure

The bones of the hand and wrist are shown in Fig. 1. The carpal bones comprise the wrist. The first metacarpal is the proximal segment in the thumb; the other metacarpals comprise the rigid skeleton determining palm shape. Each

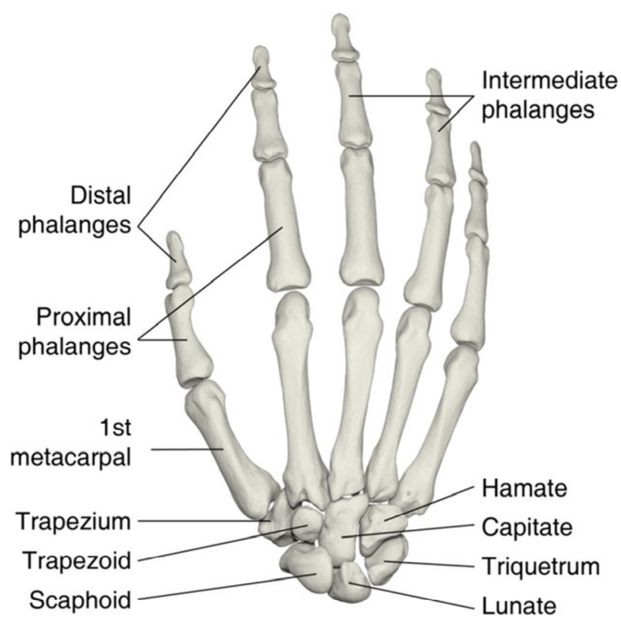

Fig. 1. Bones of the right hand, dorsal view. 3D hand bones rendered in this paper were converted from the upper limb model described in [50]. The original CT scan images from Primal Pictures, LTD were scaled to fit 50th percentile male hand proportions.

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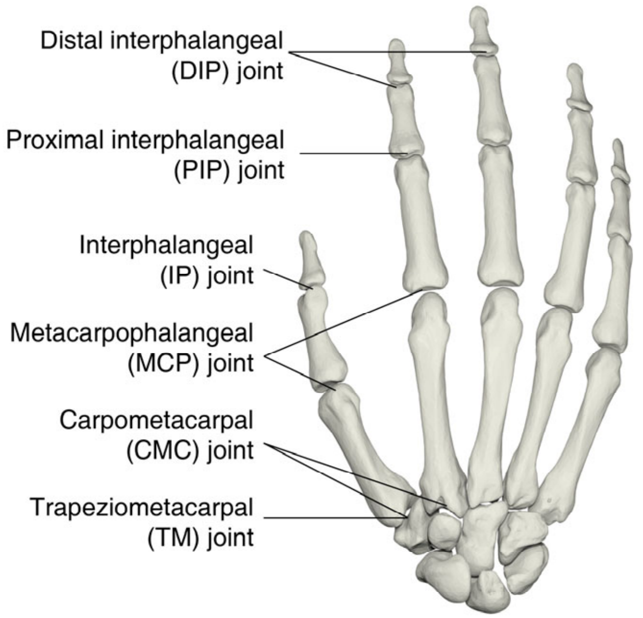

Fig. 2. Joints of the right hand, dorsal view. Note that the terms trapeziometacarpal (TM) joint and carpometacarpal (CMC) joint are both used to describe the joint between the trapezium and first metacarpal in the thumb.

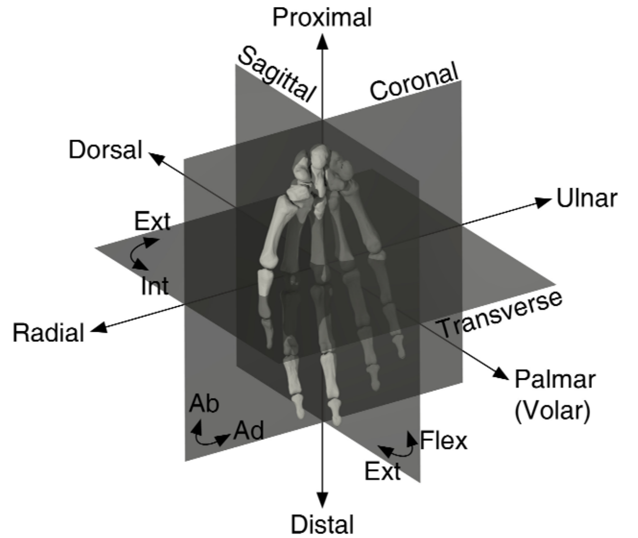

Fig. 3. Anatomical conventions for the hand (adapted from [3]). When the hand is at its standard anatomical position at the side of the body, the sagittal, coronal, and transverse planes pass through the right hand as shown. Directions are often expressed in terms of radial-ulnar, dorsal-palmar, or proximal-distal axes. Rotations are most precisely specified in terms of the anatomical planes: pure flexion-extension (Flex-Ext) occurs in the sagittal plane, abduction-adduction (Ab-Ad) occurs in the coronal plane, and external and internal rotation occur in the transverse plane.

finger has a proximal, middle, and distal phalanx, but the thumb has only a proximal and distal phalanx.

The joints of the hand can be seen in Fig. 2. The joints between the carpal and metacarpal bones are called carpometacarpal (CMC) joints. Since the first metacarpal in the thumb articulates with the trapezium, it is sometimes referred to as the trapeziometacarpal (TM) joint instead. The metacarpophalangeal (MCP) joints are found between the metacarpals and proximal phalanges. The proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints are the remaining two finger joints, while the thumb has only a single interphalangeal (IP) joint.

Several conventions are used to describe the motion of parts of the hand. The ones that will be used in this paper are illustrated in Fig. 3. The intersection of the hand with the three anatomical planes is shown, along with commonly used axes and rotation motions. The three main types of rotations are defined in terms of each of the three anatomical planes; in addition, the term *axial rotation* will be used to describe rotation that occurs around an axis along the centerline of a bone.

B. Establishing Axis Locations

If we assume that a joint can be reasonably modeled by a simple revolute (hinge) joint, the axis location is defined as the line around which purely circular trajectories of the attached rigid bodies are observed while the joint is articulated along a single degree of freedom. Note that this assumption may not hold perfectly in real human joints.

Several methods exist for finding the location and orientation of joint axes. One of the simplest methods to approximate the axes is to use the bone geometry. The articular surface shape can convey the number of degrees of freedom (DOF) for the joint, and the center of curvature of the bone head has been used to estimate joint axes (e.g. [9], [10]). A physical axis finder may also be used, in which the position of a thin wire coupled to a cadaver body segment is adjusted until only pure rotation of the wire occurs during joint articulation; the wire is then aligned with the joint axis [11]. While the axis finder method can achieve at least 1 mm, 1.5° accuracy [11] in cadaver hands, it may be less precise if applied in vivo since it cannot be rigidly attached to the bone segments.

Since soft tissue, tendons, and muscles can affect joint kinematics, and joint locations can vary between subjects, in vivo axis determination has many advantages. If the axes must be determined in vivo, then methods such as hand surface marker tracking (e.g. [12], [13]) or magnetic resonance (MR) imaging methods (e.g. [14–16]) can be used. Using MR methods, translational errors of less than 0.7 mm have been reported [15], with less than 2 mm RMS errors for the thumb [14].

Geometric principles are often used during the application of these methods to locate the joint axes. For example, Reuleaux's method [17] involves fixing one segment and performing a basic geometric construction based on two positions of the moving segment to find the joint center. Error magnification from using the method can be reduced by following certain guidelines [18].

Using one of these methods to establish axis positions or adapting existing data to fit a specific hand is necessary to specify many of the parameters for a kinematic hand model. The next section will describe in detail the kinematic models obtained by applying these methods, along with their assumptions.

III. Kinematic Hand Models and Assumptions

In this section we begin by describing general model assumptions commonly applied to all regions of the hand (III.A), followed by simplifications made for the metacarpals (III.B), fingers (III.C), and thumb (III.D).

A. General Assumptions

The Denavit-Hartenberg (D-H) convention [19] for describing kinematic chains is used for most hand kinematic models and implies assumptions that: joints can be modeled as a combination of ideal revolute joints, bones serve as perfect rigid bodies, there is a base reference frame that is fixed relative to the first joint, and that joint axes are fixed relative to their associated links (bones). Compliance in the joints, links, or base frames, as well as non-ideal rotational joint behaviors cannot be modeled directly using the D-H convention.

Other types of assumptions are also commonly used. For example, it is often assumed that certain joints can be adequately modeled by universal joints (two intersecting, orthogonal revolute joints) when in the hand the axes are not orthogonal and do not intersect. Another frequent assumption is that a single overall kinematic structure will adequately model any hand, but there is significant anatomical variability between subjects for some joints [20].

These assumptions will not hold perfectly in the real human hand but they greatly simplify kinematic and dynamic analysis. They will now be discussed in the context of specific joint models.

B. Metacarpal Models and Assumptions

The metacarpal bones, along with the carpals, form the skeletal structure of the palm. The last four carpometacarpal (CMC) joints allow a small amount of flexion-extension motion between the carpals and metacarpals. The range of motion increases from the index finger to the little finger. The little finger CMC joint is different from the other CMC joints – it is a saddle joint with an oblique axis of rotation. As this fifth CMC joint is flexed, coupled rotation and adduction occurs, producing a cupped palm shape [4].

Stillfried and van der Smagt [15] measured the motion of the CMC joints using MR imaging. Using a model with 3 revolute hinges located between the metacarpals, they recorded a range of motion of about 20° for each joint. However, many models do not allow for this significant recorded range of motion.

Models that do represent metacarpal motion typically use only the last CMC joint, represented with one rotational axis located along one of the last two metacarpals [8], [21]. Many models, such as [22–25], assume that the metacarpal positions are fixed. This is equivalent to assuming that the palm skeletal structure is completely fixed.

These common assumptions of limited or no metacarpal motion should be evaluated carefully. In applications with a large range of hand postures or significant forces applied to the hand, substantial metacarpal motion may be present. Further study of metacarpal motion could aid in understanding the role of the palm during grasping and manipulation.

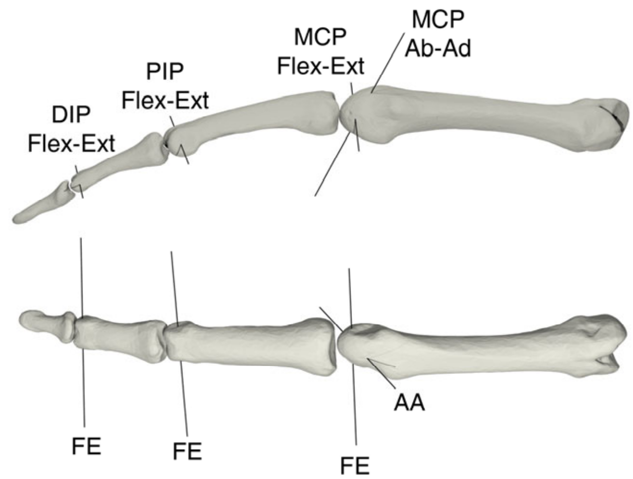

Fig. 4. Biomechanical rotation axes for the index finger (right hand). The top view is radial and the bottom view is dorsal. An axis for the CMC joint has not been shown, its motion can be represented in multiple ways.

C. Finger Models and Assumptions

Each finger has a proximal, intermediate, and distal phalanx. Each proximal interphalangeal (PIP) and distal interphalangeal (DIP) joint has a single flexion-extension axis, while the metacarpophalangeal (MCP) joint at the base of the finger has both flexion-extension and abduction-adduction axes (Fig 4).

1) Metacarpophalangeal (MCP) Joints

The two degrees of freedom of the MCP joints allow flexion-extension and abduction-adduction motions. The active flexion range is about 90° and extension can be up to 30-40°. Passive extension can reach 90° for some individuals. The abduction-adduction range is about 30°. MCP joints also show a small amount of passive axial rotation [4].

The finger MCP joint appears to always be modeled as a universal joint with orthogonal, intersecting axes [15], [22–26]. One interesting feature of MCP joint kinematics is that the proximal phalanx exhibits a large amount of coupled axial rotation with abduction-adduction motion when the digit is flexed, while large abduction-adduction motions can be performed with little axial rotation when the finger is extended [3]. Placing one of the axes at an angle aligned with the finger at 60 degrees of flexion as suggested by Brand and Hollister [3] may help to produce these characteristics of the MCP range of motion.

There is some debate in the literature about whether or not the MCP joint axes are actually fixed during finger movement. The works found that directly measure finger motion do agree that the amount of change in axis position is small. Specifically, Youm et al. [27] concluded that the joint axes are fixed within 1.5 mm, and Weiss et al. [28] observed 2.1 ± 0.8 mm of variation in the instantaneous center of rotation for the joint during a motion from 20° of extension to 90° of flexion. Some other studies modeling axis location using bone geometry and other characteristics of the MCP joint [29], [30] suggest that the instantaneous center of rotation is not fixed but do not give a concise summary of the amount of predicted variation.

A final question is whether the finger MCP joints have a third degree of freedom, or a free axial rotation (pronation/supination). Force workspace calculations in [31] suggest that a third axial rotation degree of freedom is inappropriate because it would compromise lateral force production. Although no sources were found implicating a third active degree of freedom, a passive axial rotation axis may exist. Krishnan and Chipchase [32] measured about 15° of average passive pronation and supination at each of the MCP joints when a 0.2 N·m torque was applied. The authors hypothesize that this passive rotation is important in various grasping motions and helps increase contact area between the fingers and objects [32]. However, it is unclear from the experimental methods described whether the measured motion is actually a third degree of freedom, or simply the coupled rotation that we would expect from rotation around the abduction-adduction axis of the joint. Further study might be necessary to produce decoupled measurements of this passive compliance. Many studies only consider hand postures without any external forces applied to the hand, and thus do not measure this type of passive compliance.

The finger MCP joints are generally modeled as universal joints with fixed axes. Joint axis movement can be safely ignored in many applications, but if millimeter level precision is required, a detailed understanding of axis variability may be needed. It is hypothesized that passive axial rotation at the MCP may be important to model for grasping tasks, but the currently available data is insufficient to evaluate this claim.

2) Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP) Joints

The PIP and DIP joints are one dimensional hinges between the proximal, intermediate and distal phalanges. The PIP joints actively flex more than 90° and the DIP joints slightly less than 90°. The active range of extension is almost negligible, but the DIP has an appreciable passive extension of 30°. There is also a slight passive abduction-adduction motion, especially at the DIP [4].

The PIP and DIP joint axes are not fixed. They are perpendicular to the bone segments in full extension, but become progressively oblique during flexion [4]. Few papers were found studying the variation of these axes in three dimensions. In [16], MR imaging was used to measure changes of up to 14° in the orientation of the PIP and DIP axes during motion. Tsai and Lee show in [21] that the screws defined by the finger joints vary at each joint angle, so that they describe an axode, or surface of screws. They also show that the MCP, PIP, and DIP flexion-extension axes are not parallel to each other.

Despite this variation in axis location, most sources assume planar kinematic chains for the fingers and used a single fixed axis for each joint [15], [22], [24], [25]. If a fixed axis is desired to simplify the model, Brand and Hollister [3] specify an interphalangeal axis parallel to the flexion-extension creases, slightly volar relative to the origin of the collateral ligaments. No sources were found directly comparing the accuracy of fixed and moving axis models for the DIP and PIP joints, but the error could be estimated from the axis variability measured in [16].

D. Thumb Models and Assumptions

The thumb has three joints, the trapeziometacarpal (TM) or carpometacarpal (CMC) joint, the metacarpophalangeal (MCP) joint, and the interphalangeal (IP) joint. An overall diagram of the biomechanical rotation axes of the thumb can be seen in Fig. 5. Because the TM and MCP both have two degrees of freedom and produce motion in all three anatomical planes, the thumb is particularly difficult to model.

1) Trapeziometacarpal (TM) Joint

The trapeziometacarpal (TM) joint of the thumb is a two axis joint with non-intersecting, non-orthogonal axes [33]. Although a third DOF has been proposed for the joint, this is incompatible with the saddle shape of the joint, as well as with the joint motion [33]. Cooney et al. showed that although the motion of the joint occurs in all three anatomical planes, the amount of pronation can be determined from the amount of flexion and abduction, so there are only two true DOF. This has also been confirmed in [34].

The TM axis locations were described in [33], and have been confirmed using MR imaging in [14]. Approximate axis locations can be seen in Fig. 5. Note that the flexion-extension axis passes through the trapezium, while the abduction-adduction axis is located in the first metacarpal [33].

Kinematic thumb models often use orthogonal, intersecting axes for the trapeziometacarpal joint, but this should be cautioned against for high precision applications. Cerveri et al. [13] found that RMS error for a non-intersecting, non-orthogonal model was 2.00 ± 0.38 mm,

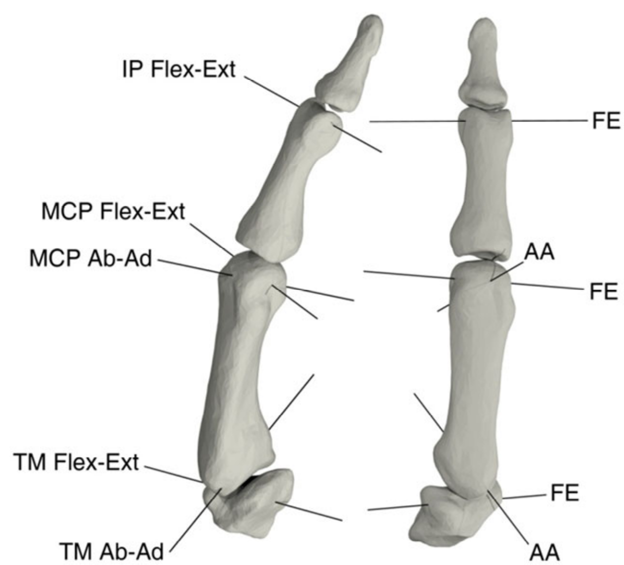

Fig. 5. Biomechanical rotation axes for the thumb, based on [2], [11], [33]. Axis locations were aligned visually based on the original anatomical diagrams, so they are not exact. Ab-Ad or AA is used as abbreviation for abduction-adduction axes, and Flex-Ext or FE is used as an abbreviation for flexion-extension axes.

whereas a universal joint model gave 3.69 ± 0.98 mm. Note that this error is only for the thumb metacarpal position, so the expected position error for the thumb tip would be significantly larger.

Current thumb models generally assume that the trapezium does not move. However, it was suggested in [3] and confirmed in [35] that the trapezium can move when loaded. Maximal FPL tension was shown to induce about 2 mm of proximal trapezium translation in a cadaver hand [35], and this is considered an underestimate of maximum trapezium translation. Adding a load dependent translational DOF to model trapezium motion could increase thumb model accuracy [36].

2) Metacarpophalangeal (MCP) Joint

Mechanical joint finder methods were used to find two non-intersecting, non-orthogonal axes for the metacarpophalangeal joint [11]. The MCP axes are difficult to define in the biological joint because the MCP always moves in coordination with the TM, since the muscles that move the MCP joint also move the TM joint [11]. Thus, it may be possible to model a healthy thumb using less than four degrees of freedom for the combined TM and MCP joint motion [3].

No sources were found directly comparing the accuracy of a universal joint model and a non-orthogonal, non-intersecting model for the thumb MCP joint. The angle between the abduction-adduction axis and flexion-extension axis is reported as 84.8 ± 12.2° in [11], so this may be close enough to 90° to assume orthogonality in some cases. Surface marker tracking, or MR imaging as in [14] could be used to evaluate how the precision is affected by using a simplified universal joint model.

Anatomical variability makes the MCP joint of the thumb particularly challenging to model. Mechanical axis finder studies measured the flexion-extension axis at 87 ± 5% and adduction-abduction axis at 83 ± 13% of the metacarpal length [11]. Running Monte Carlo simulations using this axis location data, Santos and Valero-Cuevas predicted that in 65% of models, the flexion-extension axis will be distal to the abduction-adduction, but in other cases the order of the axes will be flipped [20]. This variability in thumb kinematic structure may be related to the large variability in the range of motion of the thumb MCP joint. A bimodal distribution for flexion range of motion has been reported [37] and shown to correlate with flatness of the metacarpal head [38]. This anatomical variability may require subject-specific thumb models, or a small subset of different models, as is proposed in [20].

3) Interphalangeal (IP) Joint

There is good consensus that the thumb interphalangeal joint is best modeled as a one degree of freedom joint ([11], [39–41]). The axis of rotation for the interphalangeal joint is at 90 ± 5% of the proximal phalanx length and is parallel to the flexion creases, at a 83 ± 4° angle relative to the midline of the bone [11]. It is also at a 5 ± 2° angle relative to the palmar surface of the bone. Assuming that the thumb interphalangeal joint axis is perpendicular to the proximal phalanx will introduce angular error into the final distal link of the thumb model.

Overall, the research community appears to agree that the five link thumb model proposed in [2] is an accurate representation of the major biomechanical degrees of freedom in the thumb. Few recent sources were found which disagree that the non-orthogonal, non-intersecting axis locations that are used in the model [33], [11] are the most accurate known kinematic description. There is less consensus about which simplifying assumptions are acceptable, or what further improvements could be made to better improve the five link model.

IV. Applying Kinematic Models

In this section, we describe a few examples of how researchers in fields related to robotic grasping and manipulation, human-robot interaction, and medical areas have applied kinematic hand models.

1) Robotic Grasping and Manipulation

Because of the exceptional dexterous capabilities of the human hand, the kinematic structure of the human hand is sometimes adapted for the design of anthropomorphic robotic or prosthetic hands [42]. The most biomechanically accurate example known to the authors is the Anatomically Correct Testbed (ACT) hand, which imitates the joint axes, bone masses, and tendon routing from a human hand [39], [43], [44]. The ACT hand even uses non-orthogonal, non-intersecting axes in its thumb design [39], whereas most other robot hands user universal joints and planar kinematic chains for the fingers [45]. The ACT hand can be used to study neuromuscular control, and may have applications for prosthetics and teleoperation. The Shadow Hand, another anthropomorphic hand with 24 degrees of freedom, uses universal joints and planar fingers. The Shadow Hand is one of the few hands to implement an actuated carpometacarpal joint in the little finger [46]. However, many robot hands do not simply try to imitate the human kinematic structure.

Because of the complexity of the human hand, many robot hands use a simplified or altered kinematic structure. For example, underactuated hands [47], [48] can perform effective grasps with few actuators and minimal mechanical complexity. Some underactuated hands still try to mimic the original human finger structure, such as in [49].

The success of simplified, underactuated hands suggests that using a precise human hand kinematic structure is not the only viable approach for robot manipulation. Thus, assumptions such as using universal joints in the thumb may be less of a problem than in other domains. However, when implementing an anthropomorphic design with reduced degrees of freedom, picking which DOF to implement will greatly affect final design performance. Models of human grasping and manipulation kinematics can help inform these choices, since many objects are designed for the human hand.

2) Human Computer Interaction or Human Robot Interaction

Computer or robotic recognition of hand gestures opens a wide range of possibilities for HCI/HRI applications and allows future development of sophisticated virtual environments or augmented reality systems. However, recovering hand poses from 2D images is a challenging computational problem that requires complex object recognition and effective handling of occlusions. To speed up the computations related to the hand model, HCI researchers usually use simplified models for which there are fast algorithms to solve the kinematics and dynamics.

A widely adopted model was introduced in 1995 by Lee and Kunii [25] and has a 21 degree of freedom hand with a six degree of freedom wrist [6], [7]. The model assumes a rigid palm (fixed CMC joint angles), universal joint models for 2-DOF joints, and planar kinematic chains for the fingers. The accuracy provided by this type of simplified model may be perfectly adequate for many applications such as gesture recognition. However, when precise finger pose estimation is necessary, a formulation of the hand kinematics which at least uses the biological axis positions and degrees of freedom should likely be used.

3) Medical, Therapeutic, and Ergonomic Applications

Kinematic models based on hand biomechanics are useful in fields such as hand surgery, hand rehabilitation, and ergonomics. For example, tendon transfer surgery can be used to improve hand function after some types of hand impairments occur, but it is important to understand the force transmission of the muscles in the hand to be able to reroute tendons or muscles appropriately [3]. Hand kinematic models can be combined with muscle and tendon models, such as in [5], [50], to achieve a better understanding of both hand biomechanics and neuromuscular control. These models can then be applied to help diagnose and rehabilitate various hand impairments [51], [52]. They can even be used to design effective joint replacements that produce minimal impact on normal finger articulation [28], or to design assistive exoskeletons (e.g. [53], [54]).

Kinematic models can also be used to assess ergonomic issues with current devices or to design future products. For example, a finger force model based on a kinematic model could be used to analyze finger movements such as those used with computer input devices [55]. A hand model can also be used to predict and visualize possible grasps that will be used with a novel product, reducing the amount of user testing required in the early design stages [8], [56], [57].

V. Discussion

While some commercial robots are designed to facilitate kinematic calculations, the human hand unfortunately was not. The complex motion relationships of the hand drive many researchers to simplify the kinematics to some extent, either for the purpose of quick computation in real time applications, to provide simpler algebraic solutions, or simply to ease model implementation. While it is difficult to provide suggestions that will apply in all applications, some particular points stand out for each part of the hand.

For the metacarpals, many sources seem to assume no motion at all, when about 20° of motion can occur between each metacarpal. Metacarpals exhibit both active motion as well as significant passive compliance, so modeling the motion may be particularly important during grasping and manipulation.

Most of the simple fixed-axis, planar finger models appear to achieve acceptable accuracy, but there are still some complications that may become important in high precision applications. The MCP axis locations may vary by about 2 mm [28] during flexion-extension motions, although the exact number is unclear. The DIP and PIP axes are also not perfectly fixed, nor are they exactly perpendicular to the bone segments.

The thumb is particularly difficult to model accurately and even harder to simplify. Using orthogonal, intersecting axes for the TM joint instead of non-orthogonal, non-intersecting axes may increase positional error by up to a factor of two [13]. The MCP joint of the thumb may require multiple models due to anatomical variability of the axes [20], and it should be noted that the IP joint axis is parallel to the flexion creases rather than perfectly perpendicular to the phalanx.

There is still work to be done to understand some of the simplifying assumptions in more detail. For example, no data was found comparing the accuracy of universal joint models and non-orthogonal, non-intersecting axis models for the MCP joint of the thumb. A better characterization of trapezium movement could also improve the accuracy of thumb models.

An investigation of hand compliance in unactuated degrees of freedom could be quite useful in understanding human hand function (including grasping [58], [59] and manipulation [60]) and also for areas such as robot and prosthetic hand design. Little data appears to be available characterizing, for example, the passive rotation or abduction-adduction motions of the phalanges. While these passive motions are small, they may have an important impact on the way hand surfaces naturally conform to objects during grasping or dexterous manipulation [60], [61]. Lack of modeling of these motions is seen as a limitation of current grasp models [62].

This paper described and discussed important assumptions made in kinematic hand models, with the aim of facilitating some of the important decisions in kinematic model application. As discussed, while there are many applications in which simplified hand models are adequate, there are also many cases, such as with thumb models or CMC joint models, in which common simplifying assumptions are inappropriate and can lead to large kinematic errors. In high precision applications, effective hand modeling becomes even more challenging, since further subtle effects such as translation of the trapezium or the slight movement of various joint axes may need to be taken into account. As available hand motion sensing methods become more and more accurate, the kinematic hand model used is increasingly likely to become a limiting factor in overall accuracy.

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