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50 Benchmarks for Anthropomorphic Hand Function-based Dexterity Classification and Kinematics-based Hand Design

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Abstract—**Robotic hands with anthropomorphism considerations are of prominent popularity in human-centered environment. Existing anthropomorphic robotic hands achieving part or most of human hand comparable dexterity have been applied as various robotic end-effectors and prosthetics. However, two deficiencies are evident that the design for a dexterous anthropomorphic hand is largely based on the intuition of designers and the dexterity of robotic hand is hard to evaluate. To tackle these two challenges, this paper summarizes 50 hand dexterity benchmarks (HD-marks) to evaluate hand dexterity comprehensively from three perspectives. Secondly, a novel 22-DOFs soft robotic hand (S-22) replicates human hand kinematics is used to demonstrate all the 50 HD-marks. Thirdly, 7 critical joint-based kinematic motions (K-motions) and their correlation with the 50 HD-marks are established. Therefore, a clear robotic hand design guideline is built by mapping the hand functional dexterity to the required joint kinematics.**

I. INTRODUCTION

Anthropomorphic robotic hands have inherent advantages applied in human-centered environment [1]. One reason is that the human hand with distinctive kinematics evolved from millions of years of evolution achieving excellent dexterity provides a perfect standard for artificial hand design [2, 3]. Besides, most of the daily tools are designed based on human hand kinematics-oriented consideration [4, 5]. Reproducing human hand function has always been one of the most premier targets for roboticists to achieve. Generally, human hand function can be classified into two perspectives [6, 7]. One perspective is the prehension/motor function, which includes the physical interaction with the environments, especially as grasping and in-hand manipulation. The second perspective is the apprehension/sensory function, which includes both active and passive perception of the interaction environment, such as perception of temperature, moisture, texture, and shape. However, due to the distinctive complexity of the human hand with abundant components integrated into a small dimension, both these two perspectives have not yet been fully understood and replicated by artificial systems.

With decades of effort being devoted, achievements from both scientific and engineering societies have presented lots of excellent anthropomorphic robotic hands chasing the performance of human hand, especially at the prehension function for dexterous grasping. Typical examples are Utah/MIT Hand [8], DLR Hand [9], Gifu Hand [10], Robonaut Hand [11], i-cup Hand [12], Shadow Hand [13], BRO Hand [14], and et al. In spite of various realization approaches, the common merits of them are the capability of dexterous grasping. Most of them are able to grasp ample daily objects successfully, and parts of them are capable of realizing desired kinds of in-hand manipulation.

However, two deficiencies are evident. The first one is the overall hand dexterity is not able to be effectively evaluated and compared. The second one is the kinematics design of a desired anthropomorphic hand is largely based on the intuition of designers. These two deficiencies largely result from the lack of an effective hand-dexterity benchmarking and the lack of a proper mapping between kinematics design considerations with grasping performance.

To tackle these two challenges, this paper firstly summarizes 50 human hand dexterity benchmarks (HD-marks) from three perspectives, which include grasping, in-hand manipulation, and thumb dexterity, to evaluate anthropomorphic hand dexterity comprehensively. Secondly, a novel 22-DOFs soft robotic hand (S-22) is used to achieve all the 50 HD-marks to explore the influence of critical kinematics construction on the grasping performance. From the realization process of all HD-marks, 7 critical hand kinematics design considerations (KD-consideration) important for the grasping performance are extracted out. Based on the analysis of KD-consideration involvement in each HD-mark test, a mapping is able to be constructed between KD-consideration with hand grasping dexterity. Inversely, this mapping is beneficial to guide the dexterous anthropomorphic hand design. Thus, an effective hand dexterity benchmarking and a clear hand-design guidance are provided.

The highlight of contribution in this paper:

1. 50 hand dexterity bending marks are extracted out from three perspectives to comprehensively evaluate hand dexterity.
2. A novel 22 DOFs soft robotic hand (S-22) is used to present the realization process of all the HD-marks and provide the study platform for hand dexterity study.
3. A clear guideline for dexterous anthropomorphic hand design is drawn based on the mapping from the

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functional dexterity to the required joint kinematics.

II. HUMAN HAND DEXTERITY CLASSIFICATION AND 50 HAND DEXTERITY BENCHMARKS (HD-MARKS)

Distinctive hand dexterity of human beings is achieved by a broad scope of system cooperation that includes the coordination of hand kinematics, actuation muscles, sensing systems, and control of eyes and brain [1-5]. Each component of the overall human hand dexterity is a topic worthy to be studied and replicated by artificial systems.

For robotic hands, the hand dexterity usually refers to the mechanical functional potential, which is majorly described by the diversity of functions that the hand can achieve [6, 7]. The closely relevant performance and function have subtle differences, which helps to quantify and evaluate the dexterity of robotic hand [5-7]. Performance referred here is more related to the tasks which the dedicated robotic hand is able to achieve, the function discussed here is related to the capability of the hand to achieve the desired performance [15].

From the function perspective, there are lots of hand function classifications with considerations from different angles [16, 17]. Generally, from the difference of static and dynamic processes, robotic hand function for environmental interaction can be majorly categorized into two groups. One group is grasping, the static process, which refers to the static hand posture securely holding an object without hand orientation consideration [18-20]. The other group is in-hand manipulation, the dynamic process, which refers to the object held by hand enabled be adjusted of position and orientation [21-23]. Besides, the thumb is a distinctive digit for human hand and anthropomorphic robotic hand, which involves the most percentage of hand function. Thus, the dexterity of thumb deserves an independent consideration [24].

From the performance perspective, one viable evaluation approach is to set dedicated tasks and measure the hand prototype is able or not able to realize those tasks. Depending on the number and richness of realized tasks, the performance can be evaluated [5, 15]. Various tasks-based benchmarking approaches have been proposed in existing works for hand dexterity evaluation. However, the existing benchmarks are mostly focused on one perspective of hand function, only considered of grasping, in-hand manipulation, or thumb dexterity [24-26].

Based on the performance evaluations and function classifications, three perspectives of popular task-based hand dexterity measurements extracted out from both human hand and anthropomorphic robotic hand studies are adopted here to compose of a comprehensive hand dexterity benchmarks (HD-marks):

1. **Grasping taxonomy (33 tasks)**: Grasping taxonomy lists a series of grasping postures of human hands towards representative daily objects. A 33 score of this taxonomy is effective to measure the grasping dexterity [25, 27].
2. **In-hand manipulation taxonomy (6 tasks)**: In-hand manipulation taxonomy classifies the in-hand manipulation tasks into 6 groups depending on the three Cartesian coordinate axes [26, 28]. In each axis, there are one translation and one rotation procedure. Where in-hand here refers to the fixed wrist with only moving the fingers, palm, and the thumb.
3. **Thumb dexterity (11 tasks):** Thumb is a distinctive construction of human hand and it has the highest involvement of hand functions compared to other fingers. It is essential to individually evaluate dexterity. Kapandji test provides a popular task-based procedure that includes 11 scores to evaluate the thumb dexterity [24].

Thus, overall 50 hand dexterity benchmarks (HD-marks) are synthesized to comprehensively evaluate the hand dexterity. The full score represents a human hand level comparable dexterity. The achieving of all these 50 HD-marks used to evaluate the hand dexterity will be discussed in Section III.C. The HD-mark also functions as a reference list for intended robotic hand function assisting the design of robotic hand, which will be discussed in Section V.

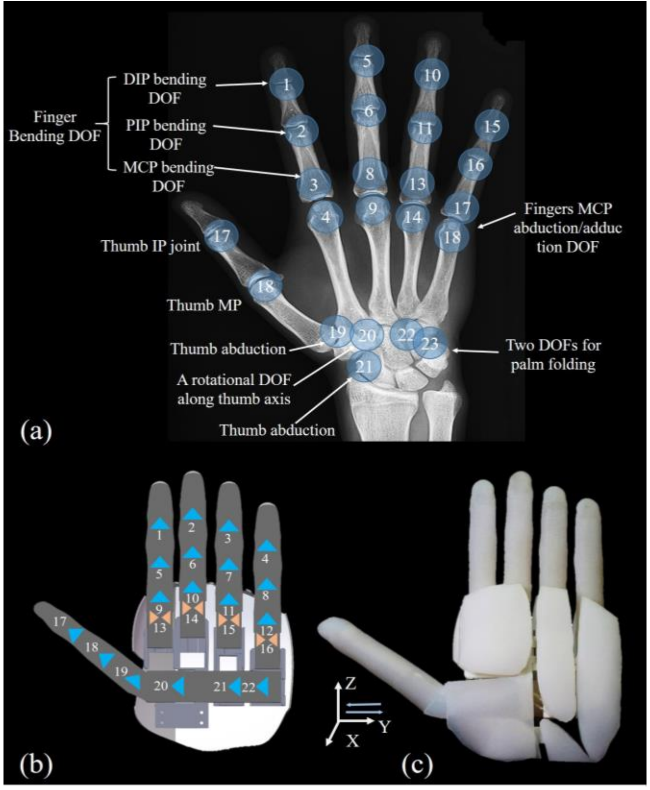

Figure 1. Human hand kinematics and its replication. (a) The illustration of hand 23 DOFs distribution of human hand. (b) The illustration of hand 22 DOFs distribution of S-22. (c) Real S-22 prototype.

III. A HUMAN HAND KINEMATIC REPLICATED SOFT HAND ACHIEVES ALL THE HD-MARKS

A. Human Hand Kinematic Analysis and Replication

The key feature that enables human hand dexterity is the contained degree of freedoms arranged in the desired order (DOFs) [6, 7]. In order to repeat human hand dexterity, it is essential to replicate human hand DOFs accordingly and

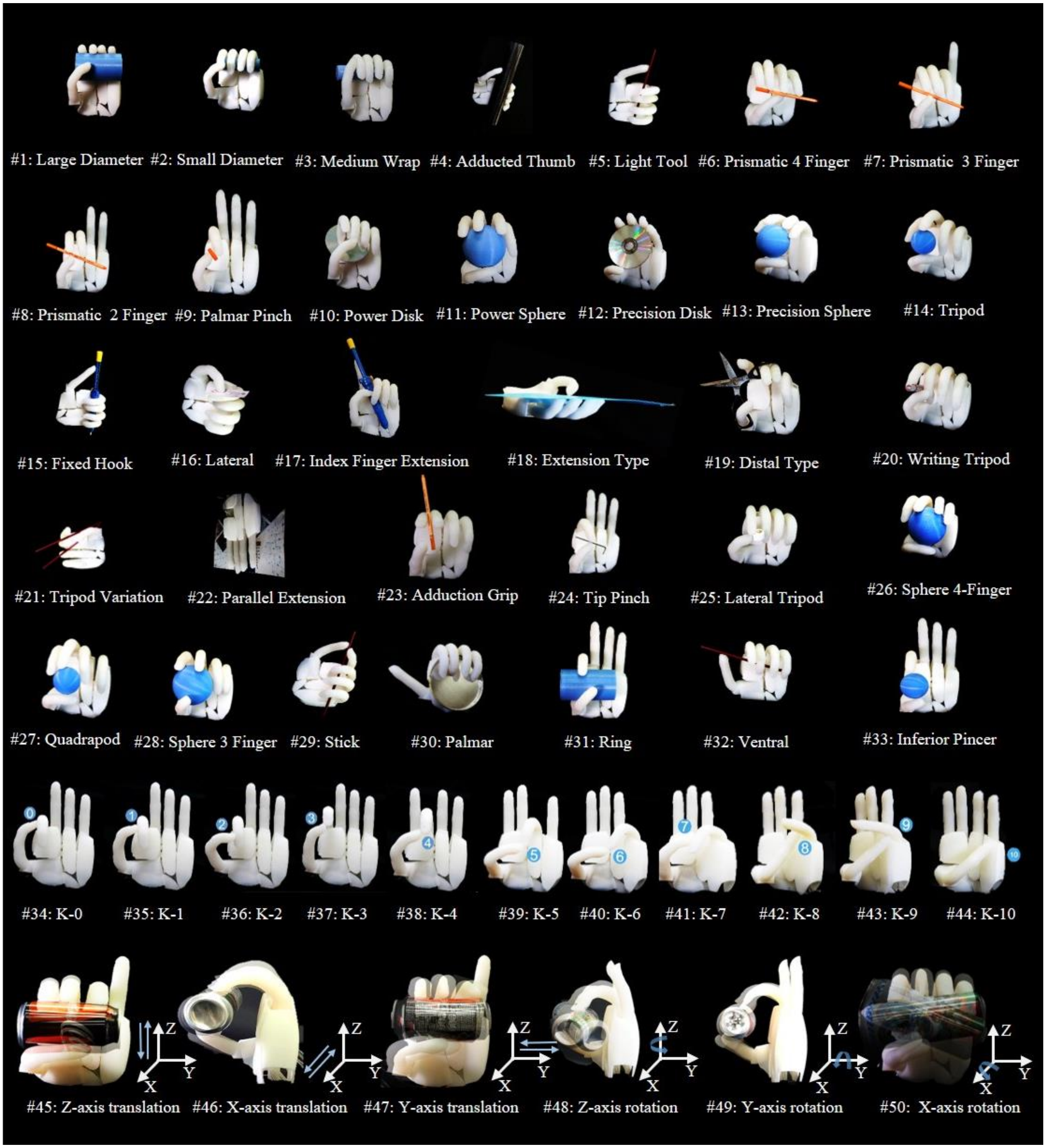

Figure 2. 50 hand dexterity benchmarks (HD-marks) achieved by S-22: (#1-33) present the realization of 33 grasping taxonomy tasks. (#34-44) present the achieving of 10 Kapandji tests. (#45) presents the Z-axis translation. (#46) presents the X-axis translation. (#47) presents the Y-axis translation. (#48) presents the Z-axis rotation. (#49) presents the Y-axis rotation. (#50) presents the X-axis rotation.

effectively.

A commonly accepted 23-DOF human hand model is selected as the replicating target [29]. Because DOF 21 is the thumb rotation that contributes the least among all the DOFs in hand daily performance [29], we exclude this DOF out from our target robotic hand model. Thus the target kinematic of our soft hand should contain the left 21 DOF accordingly.

Traditional rigid robotic hands usually realize multi-DOFs by connecting pin joints with rigid links in the desired arrangement [8-13]. However, the actuation for multi-joint at the same time is a challenge. Underactautuion mechanism is effective to provide a simultaneous actuation for multi rigid joints, but the highly coupled joints motion hampers the system dexterity [16]. Fully actuation for rigid robots needs

Table I. 7 Basic Hand Kinematics Motions (K motion) and their involved joints motion/DOFs

Influential factors KD-Consideration		Basic Involved Joints/DOFs	Advanced Design Factors
I.	**Finger Bending * n** (n is the number of fingers ranges from 1 to 4)	At least one bending joint per finger. (One joint of SD-(1-3) for the index finger)	Two to three bending joints per finger. (SD-(1-3) for the index finger)
II.	**Finger Abduction/Adduction**	One joint for Ab/Ad per finger. (SD-4 for index finger)	Nul
III.	**Thumb Bending**	At least one bending joint for thumb. (one of SD-(17-18))	Two bending joints for thumb. (SD-(17-18))
IIII.	**Thumb Abduction/Adduction**	One joint of Ab/Ad for the thumb. (SD-19)	Nul
V.	**Thumb Folding**	One folding joint for the thumb. (SD-21)	Nul
VI.	**Palm Folding**	One DOF of palm folding. (One of SD-(22-23))	Two DOF of palm folding. (SD-(22-23))
V\II.	**Independent Joint Actuation**	Independent actuation for each DOF of the fingers and the thumb.	Nul

one actuator for each DOF, which inevitably results in a bulky and complex system in a compact hand space [3, 4].

B. A Human Hand Kinematics Replicated 22-DOFs Soft Robotic Hand (S22)

Soft robotic technology merges the boundary of the actuator and manipulator [30], which provides an effective solution for multi-DOF soft actuator design. A refinement is applied to our previous multi-DOF soft actuator design [31-33]. Dissymmetry chamber design, V-joint as depicted in Fig 1, is used for each chamber. Thus each joint performs a relative sharp bending like a human finger joint. By arranging these V-joints in the desired order, versatile soft robots can be assembled in a compact structure with an integrated actuator and manipulator body [34].

Based on the multi-DOF soft actuator fabrication approach, an anthropomorphic hand (S-22) is fabricated out with 22 DOFs rigorously imitating the human hand DOFs distribution. The kinematics of the proposed S-22 is illustrated in Fig 2. All the contained 22 DOFs are able to be independently actuated. The details of multi-channel pneumatic actuation and control of S-22 are discussed in our previous work [34-40]. The specific DOF is expressed as Soft DOF (SD) following the DOF number.

With S-22, the 22 DOF anthropomorphic soft hand capable of independent joint actuation, the study of the hand dexterity evaluation, and the relationship of performance dexterity and hand kinematics are possible to be processed.

C. S-22 Achieves All the 50 HD-marks

As discussed in Section II, 50 HD-marks are extracted out to comprehensively evaluate hand dexterity. The S-22 hand is successfully achieved all the 50 HD-marks tasks as depicted in Fig 3. Tasks #1-33 are the 33 grasping taxonomy tests toward daily objects. Tasks #34-44 are the 11 Kapandji score tests for the thumb dexterity. Tasks #45-50 present the 6 basic types of in-hand manipulation.

For each task realization, we first realized the task by human hand (Three Lab members repeat the task manually) several times and analyzed the required involved hand DOFs and their function order. Then, the directly related DOFs of S-22 and three function orders were programmed for S-22. For grasping taxonomy tests, the judging standard of successful grasping realization was the stable objects grasping holding for 10 seconds. For Kapandji test, the judging standard of successful thumb dexterity realization was the stable holding of dedicated gesture for 10 seconds. The In-hand manipulation tasks were dynamic processes, the successful judgment standard of which was the stable and smooth in-hand manipulation with the desired manipulation range. All the dynamic process of 50 HD-marks are presented in the accompanying video.

IV. 7 KINDS OF BASIC HAND KINEMATICS MOTION

After the realization of 50 HD-marks by S-22, an analysis is able to be processed based on the kinematics construction for the final grasping dexterity. The basic units of kinematics are the distributed joints/DOFs. Because each function needs the cooperation of multi-DOFs together, it is not effective to map from individual joint/DOF to grasping dexterity directly. A better approach is to extract out basic hand motion which composed of dedicated DFOs and construct the dexterous hand function. Following this intuition, 7 basic hand kinematics motions (K-motion) are extracted out to function as the bridge to link the basic kinematics unit, joints/DOFs, to the grasping dexterity. The 7 K-motions are:

1. **Finger Bending**: The primary fingers, index, middle, ring, and little finger, bending with at least one DOF per finger.
2. **Finger Abduction/Adduction**: The capability of bi-lateral motion perpendicular to the finger bending direction.
3. **Thumb Bending**: The thumb bending with at least one DOF per finger.
4. **Thumb Abduction/Adduction**: The capability of bi-lateral motion perpendicular to the thumb bending direction.
5. **Thumb Folding**: The capability of thumb folding towards the position opposable to fingers.
6. **Palm Folding**: The capability of palm folding for integrating fingers closely.
7. **Independent Joint Actuation**: The actuation relationship between cooperated joints/DOFs.

Table II. Correlation between 7 K-motions and 50 HD-marks (K-HD Involvement)

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17
I	H*4	H*4	H*4	H*4	H*4	H*4	H*3	H*2	H*1	H*4	H*4	H*4	H*4	H*3	H*4	H*2	H*2
II	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	H
III	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
IIII	R	R	H	H	H	H	R	R	R	R	R	R	R	R	N	N	N
V	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	N
VI	N	N	N	N	N	N	N	N	N	H	H	H	H	N	N	N	N
VII	R	H	H	H	H	R	R	R	R	R	R	R	R	R	R	R	R
	#18	#19	#20	#21	#22	#23	#24	#25	#26	#27	#28	#29	#30	#31	#32	#33	#34
I	N*4	H*3	H*2	H*2	N*4	H*2	H*1	H*3	H*4	H*3	H*3	H*3	H*3	H*3	H*3	H*3	H*2
II	N	H	H	H	N	H	N	H	H	R	R	R	R	R	R	R	N
III	H	H	H	H	H	N	H	R	R	R	R	R	R	R	H	H	H
IIII	H	H	H	H	H	N	R	H	H	R	R	R	R	R	R	R	R
V	H	H	H	H	H	N	R	H	H	H	H	H	H	H	H	H	H
VI	N	N	H	H	N	N	N	N	H	N	N	N	N	N	N	N	N
VII	N	H	H	H	R	R	R	R	R	R	R	R	R	R	R	R	R
	#35	#36	#37	#38	#39	#40	#41	#42	#43	#44	#45	#46	#47	#48	#49	#50	
I	H*1	H*1	H*1	H*1	H*1	H*1	H*1	H*1	H*1	H*1	H*3	H*4	H*3	H*2	H*2	H*4	
II	R	R	R	R	R	R	R	R	R	R	H	H	H	H	H	H	
III	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	
IIII	R	R	R	R	R	R	R	R	R	R	H	H	H	H	H	H	
V	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	
VI	R	R	R	R	H	H	H	H	H	H	H	R	R	R	R	R	
VII	R	R	R	R	R	R	R	R	R	R	H	H	H	H	H	H	

H= Highly Required. R=Relevant. N= Not relevant. (For K-motion I, *n means the number of upper fingers involved)

The involved joints/DOFs of each K-motion are listed out in Table I. To achieve the intended K-motion, the related DOFs are desired in the design consideration.

V. INVOLVEMENT OF 7 K-MOTIONS IN 50 HD-MARKS

A. 7 K-motions Involvement Analysis

After the extraction of 7 K-motions, it is beneficial to analyze the involvement of the K-motion in the 50 HD-marks, which provides clues of how K-motion functions in each HD-mark.

The analysis process was composed of two steps. The first step was analyzing the realization process of the 50 HD-marks by the human hand, which provides the standard and example for S-22 to imitate as presented in Fig 2. Secondly, from only task success consideration, sometimes the robotic hand is able to successfully achieve the same task in a relatively simpler manner compared to the human hand approach. Thus, the S-22 hand was used to repeat the task again involving minimum actuated Joints/DOFs and using as far as possible coupled joints actuation to achieve the intended task again.

Three levels of involvement for K-motions in each HD-mark are classified. The first level is "Highly Required", which means the specific K-motion is necessarily required to achieve the related HD-mark. The second level is "Relevant", which means the involvement of the K-motion will help the hand to achieve the dedicated HD-mark better but the hand will also achieve the task without this K-motion. The third level is "Not Relevant", which represents the K-motion is not a relevant motion required to achieve the dedicated HD-mark.

The analysis result is summarized in Table II. The HD-marks are listed in a row with number #n (n=1-50) in the same order as depicted in Fig 2. Seven lines present the involvement of 7 K-motions illustrated in Table I with 3 levels of importance. This result can be easily extended by adding more HD-marks from desired hand functional considerations and repeat the 7 K-motions analysis process.

B. K-motions Involvement Result Discussion

Firstly, the K-HD Involvement result provides the K-motion requirement preference/difference of the three hand dexterity perspectives, grasping, in-hand manipulation, and thumb dexterity.

For daily objects grasping, 3 of 7 K-motions are especially necessary, which are the upper finger bending, thumb bending, and thumb folding. These three K-motions exist in all the 33 grasping HD-marks. If composing these 3 K-motions (with four upper fingers), 31 of 33 grasping HD marks are still able to be achieved except mark #5 (light tool) and #19 (Distal type). Light tool grasping needs the finger pad squeezing to achieve a close region for holding of which. S-22 can achieve light tool holding by finger-tips pressing the tool onto the palm, which requires the joint independent actuation. This result is in accordance with the performance reported by other published soft hand, which constructed by four upper fingers, a bending thumb, and a thumb folding joint mounted with the palm together. For distal type grasping, fingers abduction/adduction are required to move the scissors in desired direction. The dynamic process and illustration are presented in the accompanying video of this paper.

As far as Kapandji test, the above discussed three K-motions crucial for grasping are also important. Compared to grasping HD-marks, the palm folding is further required especially for Kapandji score #5-10. Palm folding is beneficial to shorten the distance between the thumb and upper fingers.

For in-hand manipulation, except for palm folding, all other 6 K-motions are highly required. In contrast to the above two perspectives, in-hand manipulation imposes the highest kinematics requirements. Joint independent actuation is the evident feature to achieve common workspace between fingers, which is crucial for object manipulation. Specifically, for each finger, there are at least two independent bending joints for in-hand manipulation.

Secondly, the K-HD Involvement result provides the information about required K-motions for specific tasks. For example, given a specific design intention towards several intended tasks among HD-marks, it is possible to check out the required K-motions to achieve these tasks. Then, the required K-motions can be found in their related joints/DOFs as illustrated in Table I. By replicating these joints/DOFs, the proposed hand is potential to achieve the intended tasks. As a result, following this K-motion and HD-marks relationship, it is possible to guide the hand design.

VI. HAND KINEMATICS BASED DESIGN GUIDANCE TO FUNCTIONAL DEXTERITY

Following the discussion in Section V, this section provides the specific operation steps of kinematics-based anthropomorphic hand design, which based on the K-HD Involvement analysis. Three preliminary examples are provided with hand dexterity verification in our previous work.

A. Kinematics Based Hand Dexterity Design Process

The hand dexterity design guidance includes 5 steps as depicted in Fig 3(a). The first step is to define the intended hand dexterity/function based on the application intention. With this intention, it is effective to check the related tasks from 50 HD-marks as depicted in Fig 2. After selecting out the related HD-marks, it is possible to summarize out the required K-motions illustrated in Table I. Then, K-motion can function as the bridge to link the function with the hand kinematics as depicted in Table I. By extracting the required Joints/DOFs constructed the desired K-motions, the requirement of the intended robotic hand is provided. Through rearranging the extracted Joints/DOFs in the desired order with anthropomorphism consideration, the intended robotic hand kinematics is presented.

B. Example of Kinematics Based Dexterous Hand Design

Three specific examples of the kinematics based dexterous robotic hand design are presented in this section.

Towards a hand intended for general daily objects grasping, the related HD-marks are the 33 grasping taxonomy tasks (#1-33 of fig 2). The involvement of K-motions in these grasping tasks, as discussed in Section V.B, is majorly the finger bending, thumb bending, and thumb folding. Checking the related DOFs composed of the required K-motions, each K-motion requires at least one DOF. Based on this basic kinematics requirement, one example of the intended hand kinematics is presented in Fig 3(b) [32, 34].

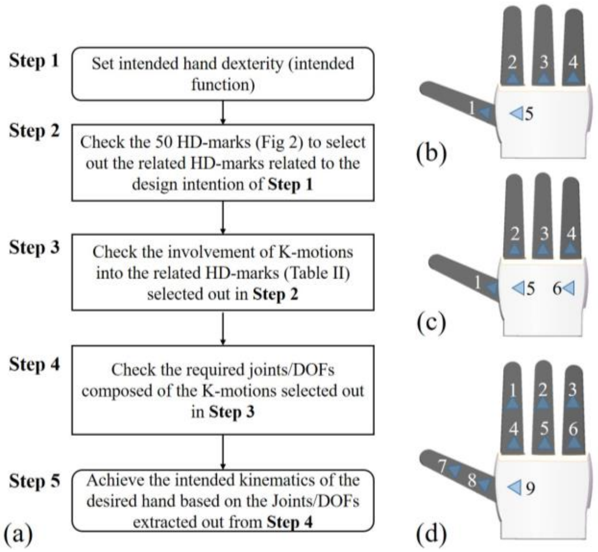

Figure 3. (a) The steps of proposed kinematics-based hand design. (b) Basic 5- DOFs hand kinematics for daily objects grasping. (c) Basic 6-DOFs hand kinematics for Kapandji test. (d) Basic 9-DOFs hand kinematics for in-hand object manipulation.

If the hand is designed to achieve all the Kapandji test, the related HD-marks are the 10 Kapandji score tasks (#34-44 of fig 2). The involvement of K-motions in these grasping tasks, as discussed in Section V.B, are majorly the finger bending, thumb bending, thumb folding, and palm folding. Checking the related DOFs composed of the required K-motions, each bending K-motion requires at least one DOF. Based on this basic kinematics requirement, one example of the intended hand kinematics is presented in Fig 3(c) [32, 34].

For a hand intended for in-hand manipulation, the related HD-marks are the 6 in-hand manipulation tasks (#45-50 of fig 2). The involvement of K-motions in these manipulation tasks, as discussed in Section V.B, are all other 6 K-motions except the palm folding. Checking the related DOFs composed of these required K-motions, each bending K-motion requires at least two DOF with independent joint actuation. Based on this basic kinematics requirement, one example of the intended hand kinematics is presented in Fig 3(d) [32, 34].

VII. CONCLUSION AND FUTURE WORK

In this paper, we present an artificial hand dexterity evaluation approach with 50 benchmarks summarized from three perspectives, grasping (33 scores), in-hand manipulation (6 scores), and thumb dexterity (11 scores). The evaluation of hand dexterity based one the 50-HD marks is discussed. A novel soft hand with 22 DOFs mimicking human hand kinematics achieves all these 50 benchmarks is presented with kinematics design illustration. The realization of each benchmark has been discussed and presented. In each evaluation task, the major involved DOFs have been analyzed. Based on the 50 benchmarks realization process analysis, a relationship between hand-design factors and dexterity performance is summarized out. Two general design factors are crucial for artificial hand dexterity, which are the DOF distribution and DOF actuation independence.

Future work includes: Constructing more data-poor for more artificial hands based on the proposed dexterity benchmarks; Including further perspectives of dexterity evaluation tasks; Exploring more detailed relationship between artificial hand-design considerations and functional dexterity.

REFERENCES

[1] Alami R, Albu-Schäffer A, Bicchi A, et al. Safe and dependable physical human-robot interaction in anthropic domains: State of the art and challenges. IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 2006: 1-16.

[2] Chen W, Xiong C, Huang X, et al. Kinematic analysis and dexterity evaluation of upper extremity in activities of daily living. *Gait & Posture*, 2010, 32(4): 475-481.

[3] Piazza C, Grioli G, Catalano M G, et al. A century of robotic hands. Annual Review of Control, *Robotics, and Autonomous Systems*, 2019, 2: 1-32.

[4] Biagiotti, L., Lotti, F., Melchiorri, C., & Vassura, G. How far is the human hand? a review on anthropomorphic robotic end-effectors, 2004.

[5] Watanabe, Tetsuyou, Kimitoshi Yamazaki, and Yasuyoshi Yokokohji. "Survey of robotic manipulation studies intending practical applications in real environments-object recognition, soft robot hand, and challenge program and benchmarking." Advanced Robotics 31.19-20 (2017): 1114-1132.

[6] Bicchi A. Hands for dexterous manipulation and robust grasping: A difficult road toward simplicity. *IEEE Transactions on robotics and automation*, 16(6): 652-662, 2000.

[7] Cutkosky M R. On grasp choice, grasp models, and the design of hands for manufacturing tasks. *IEEE Transactions on robotics and automation*, 5(3): 269- 279, 1989.

[8] Jacobsen S, Iversen E, Knutti D, et al. Design of the Utah/MIT dextrous hand. Proceedings. 1986 IEEE International Conference on Robotics and Automation. IEEE, 1986, 3: 1520-1532.

[9] Butterfaß J, Grebenstein M, Liu H, et al. DLR-Hand II: Next generation of a dextrous robot hand. Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation (Cat. No. 01CH37164). IEEE, 2001, 1: 109-114.

[10] Kawasaki H, Komatsu T, Uchiyama K. Dexterous anthropomorphic robot hand with distributed tactile sensor: Gifu hand II. *IEEE/ASME transactions on mechatronics*, 2002, 7(3): 296-303.

[11] Lovchik C S, Diftler M A. The robonaut hand: A dexterous robot hand for space. Proceedings 1999 IEEE international conference on robotics and automation (Cat. No. 99CH36288C). IEEE, 1999, 2: 907-912.

[12] Schmitz A, Pattacini U, Nori F, Natale L, Metta G, Sandini G. 2010. Design, realization and sensorization of the dexterous iCub hand. In 2010 10th IEEE-RAS International Conference on Humanoid Robots, pp. 186–91. New York: IEEE.

[13] Shadow Robot Co. 2018. Shadow Dexterous Hand. Shadow Robot Company. https://www.shadowrobot. com/products/dexterous-hand.

[14] Deimel R, Brock O. 2016. A novel type of compliant and underactuated robotic hand for dexterous grasping. Int. J. Robot. Res. 35:161–85.

[15] Vazhapilli Sureshbabu A, Metta G, Parmiggiani A. A Systematic Approach to Evaluating and Benchmarking Robotic Hands—The FFP Index. Robotics, 2019, 8(1): 7.

[16] Dollar A M, Howe R D. The highly adaptive SDM hand: Design and performance evaluation. *The international journal of robotics research*, 2010, 29(5): 585-597.

[17] Jacobson C, Sperling L. Classification of the hand-grip: a preliminary study. *Journal of Occupational and Environmental Medicine*, 1976, 18(6): 395-398.

[18] Bicchi A, Kumar V. Robotic grasping and contact: A review. Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings). IEEE, 2000, 1: 348-353.

[19] Bicchi A. On the closure properties of robotic grasping. *The International Journal of Robotics Research*, 1995, 14(4): 319-334.

[20] Ciocarlie M T, Allen P K. Hand posture subspaces for dexterous robotic grasping. *The International Journal of Robotics Research*, 2009, 28(7): 851-867.

[21] Yousef H, Boukallel M, Althoefer K. Tactile sensing for dexterous in-hand manipulation in robotics—A review. *Sensors and Actuators A: physical*, 2011, 167(2): 171-187.

[22] Sudsang A, Srinivasa N. Grasping and in-hand manipulation: Geometry and algorithms. *Algorithmica*, 2000, 26(3-4): 466-493.

[23] Humphry R, Jewell K, Rosenberger R C. Development of in-hand manipulation and relationship with activities. *American Journal of Occupational Therapy*, 1995, 49(8): 763-771.

[24] Kapandji A. Clinical test of apposition and counter-apposition of the thumb. Annales de chirurgie de la main: organe officiel des societes de chirurgie de la main, 1986, 5(1): 67-73.

[25] Feix T, Romero J, Schmiedmayer H B, et al. The grasp taxonomy of human grasp types. *IEEE Transactions on Human-Machine Systems*, 2015, 46(1): 66-77.

[26] Bullock I M, Ma R R, Dollar A M. A hand-centric classification of human and robot dexterous manipulation. I*EEE transactions on Haptics*, 2012, 6(2): 129-144.

[27] Feix T, Pawlik R, Schmiedmayer H B, et al. A comprehensive grasp taxonomy. Robotics, science and systems: workshop on understanding the human hand for advancing robotic manipulation. 2009, 2(2.3): 2.3.

[28] Lee, Dong-Hyuk, et al. "KITECH-hand: A highly dexterous and modularized robotic hand." *IEEE/ASME Transactions on Mechatronics* 22.2 (2016): 876-887.

[29] J. R. Napier and R. H. Tuttle, Hands. Princeton, NJ, USA: *Princeton* Univ. Press, 1993.

[30] Rus D, Tolley M T. Design, fabrication and control of soft robots. *Nature*, 2015, 521(7553): 467-475.

[31] Zhou J, Chen S, Wang Z. A Soft Robotic Gripper with Enhanced Object Adaptation and Grasping Reliability. *IEEE Robotics & Automation Letters*, 2017, 2 (4):2287-2293.

[32] Zhou J, Yi J, Chen X, et al. BCL-13: A 13-DOF Soft robotic hand for dexterous grasping and in-hand manipulation. *IEEE Robotics and Automation Letters*, 2018, 3(4): 3379-3386.

[33] Zhou J, Chen Y, Chen X, et al. A proprioceptive bellows (PB) actuator with position feedback and force estimation. *IEEE Robotics and Automation Letter* 2020;5:1867–1874.

[34] Zhou J, Chen X, Chang U, et al. A Soft-Robotic Approach to Anthropomorphic Robotic Hand Dexterity. *IEEE Access*, 2019, 7: 101483-101495.

[35] Zhou J, Chen X, Li J, et al. A soft robotic approach to robust and dexterous grasping. 2018 IEEE International Conference on Soft Robotics (RoboSoft). IEEE, 2018: 412-417.

[36] Zhou J, Chen X J, Chang U, et al. Intuitive control of humanoid soft-robotic hand BCL-13. 2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids). IEEE, 2018: 314-319.

[37] Zhou J, Chen X J, Chang U, et al. A grasping component mapping approach for soft robotic end-effector control. 2019 2nd IEEE International Conference on Soft Robotics (RoboSoft). IEEE, 2019: 650-655.

[38] Zhou J, Chen Y, Hu Y, et al. Adaptive Variable Stiffness Particle Phalange for Robust and Durable Robotic Grasping. *Soft Robot*, 2020 10.1089, Apr 22.

[39] Yi, J., Chen, X., Song, C., Zhou, J., Liu, Y., Liu, S., & Wang, Z. Customizable three-dimensional-printed origami soft robotic joint with effective behavior shaping for safe interactions. 2018. *IEEE Transactions on Robotics*, 35(1), 114-123.