FULL PAPER

Mechatronic Designs for a Robotic Hand to Explore Human Body Experience and Sensory-Motor Skills: a Delphi Study

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ABSTRACT
To bridge the gap between users' expectations and technological solutions, a better understanding of human body experience and sensory motor skills is mandatory. This could pave the way towards a novel generation of robotic hands, which can be successfully employed in everyday life e.g. in prosthetics and assistive robotics. Available robotic hands are still far from matching the requirements of the corresponding experimental and real-world applications, e.g., fast motions might be achieved at the expense of accuracy. Knowledge of the users' sensory-motor skills can guide technical developments, e.g., prosthetic design processes. This paper presents design solutions developed in a Delphi study. Explorative questionnaires are prepared to acquire and elaborate expert opinions to improve the design of previously developed robotic anthropomorphic hands. By gathering and fusing expert opinions, novel robotic hand and wrist concepts specifically optimized regarding body experience and sensory-motor skill research are developed. In three rounds, experts with experience in robotic hand design and/or control analyze, develop, and rank solutions for mechanisms, actuators, and control , which result in overall design concepts. The technical concepts and implications resulting from the study are discussed considering psychological and biomechanical aspects.

KEYWORDS
Robotic hand design; human body experience; sensory-motor skills; expert study; assistive robotics

1. Introduction

The human body and human body expeirence represent extraordinary sources of inspiration for robotics. Increasing the knowledge of the mechanisms underpinning the astonishing sensory-motor skills of humans could be the key for an effective design of wearable robotic devices, especially to increase users' acceptance and device embodiment [1].

A crucial topic in assistive robotics is the human body schema, which is a psychological concept describing a subconscious and neurophysiological representation of

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the characteristics of one's own body [2,3]. Successful embodiment of artificial devices requires an effective multisensory integration of visual, tactile, motor, and proprioceptive information [4]. One of the most influential experimental paradigms to investigate such effects is the Rubber Hand Illusion (RHI) [5]. In this experiment, the hidden real hand of the participant and a visible rubber hand are presented with synchronous tactile stimulation. Through multisensory integration, a feeling of body-ownership regarding the rubber hand emerges. Fundamental psychological studies explored factors that influence the integration effect, e.g., form [6] and skin tone [7]. The introduction of robotic hands extended the capabilities of such paradigms for psychological research, especially regarding the manipulation of multisensory stimulation [8–10]. Beyond this, it opened up applications for the design of robotic devices that interact tightly with human users, e.g., assistive and rehabilitation robotics [1,11].

Under this regard, broader neuroscientific investigation of human behavior could provide successful guidelines for the development of artificial systems close to users' expectations and capabilities. This particularly applies to the design of robotic hands which should behave similarly to their biological counterparts. To this end, it is worth mentioning the concept of synergies, i.e., low dimensional principal control-actuation patterns, which has been extensively studied in literature as a mean that the human brain relies on to cope with biomechanical complexity of our limbs [12]. Interestingly, synergy-inspired reduction approaches have also inspired the realization of simplified control and hardware architectures [13–17]. A notable implementation of synergistic concept which combines under-actuation and adaptability is the Pisa/IIT SoftHand [18]. It uses only one motor and constraints the free motion along the most used human grasping patterns [19], but it is adaptable and deforms to mold around and grasp a wide range of arbitrary items thanks to the intrinsic compliance embedded in the hand structure. Due to its simple and effective design, it has been suggested for translation into a prosthetic version [20]. Various other concepts of under-actuation and a technical implementation that allows to drive 16 joints with 5 actuators are presented in [21]. Particularly, synergies can guide the enforcement of inter-digit coordination, which can be implemented mechanically or by means of control [22]. Besides tailoring design and control to specific motion tasks, the concept of synergies also enables controllers to map human hand motions onto robotic hands with dissimilar kinematics [23,24].

An analysis of the requirements of human-in-the-loop experiments targeting embodiment showed that most robotic devices used in such experiments exhibit proprietary designs and controls [10]. The technical solutions applied in psychology-related literature are less sophisticated or do not represent the full capabilities of the human hand [25–27]. Moreover, the results on the influence of haptic feedback are contradictory [28,29]. Hence, it appears very promising to support psychological and biomechanical experiments targeting assisitve applications as well as the neuroscientific investigation on human sensory-motor control by a tailored robotic hand.

To overcome recent issues, this paper presents the outcome of a three-stage Delphi study [30] involving international robotic hand design and control experts. Based on the fused expert opinions, a novel robotic hand and wrist concept that is specifically optimized regarding body experience and sensory-motor skill research is developed. The paper describes the study design, how consensus was made, the development of the decision, and the final design outcome.

2. Methods

To determine robotic hand and wrist concepts that are specifically optimized regarding body experience and sensory-motor skill research, a Delphi study was set up.

The Delphi method asks for opinions of experts from the particular field and is especially recommended for fundamental and long-term design studies in engineering [30]. It is also applied to integrate expert opinions in scientific research, e.g., in rehabilitation research [31,32]. While [30] suggests to ask the experts for written conceptual response, [31,32] use questionnaires, which enables quantitative evaluation. During three rounds, the participating experts develop the design concept by consensus [30]. According to [30], such studies need careful planning and "are confined to general problems bearing on fundamental questions".

Although various robotic limb designs exist, e.g., [21,22,33], tailoring such devices to facilitate body experience and sensory-motor skill research is such a fundamental issue. The presented study gathers and explores expert opinions with online questionnaires comprising selection items and free text responses. The opinions are fused based on consensus of the experts in three rounds. The resulting device is intended to serve as a tool to research human body experience and sensory-motor skills and hence does not necessarily need to meet the requirements of every-day use.

2.1. Participants

The participating experts were recruited from the research network of all authors. The inclusion criterion was in-depth experience in robotic hand design and/or control through longer-term involvement in academic groups with a corresponding research focus and experience in device design for human studies and applications. Thirtyeight (38) international experts were invited via email to participate in the Delphi study. In the first round, the experts were asked to indicate their professional background and leave their email contact for invitation to the subsequent rounds. In all rounds, data of participants who did not respond to each question was excluded from evaluation.

Fourteen ($N_1 = 14$) experts from Belgium, Denmark, France, Germany, Italy, and the USA completed the first round. The second and third round was completed by $N_2 = 12$ and $N_3 = 13$ of these experts, respectively. This complies with the response rates of similar Delphi studies [31,32]. The group of experts who completed the first round comprises 4 professors (28.57%), 2 senior/tenured researchers (14.29%), 1 post-doctoral researcher (7.14%), 5 PhD students (35.71%), and 2 engineers working in academia (14.29%). Their professional backgrounds include mechanical engineering, electrical engineering, computer science, mechatronics, biomedical engineering, control engineering, robotics, and haptics, who are also experienced in human studies and applications.

This study was conducted without the recommendations of an ethics committee since the experts were not reporting about personal information but only judged technical design options. All participants were informed about the design of the study and that their individual feedback is kept anonymous as well as that only statistically evaluated results will be published. Before taking part, all experts gave informed consent by activating a checkbox stating "I, confirm my participation in this survey."

Table 1. Agreement levels as presented in [36].

κ-value	Agreement level
$\kappa \leq 0.2$	Poor agreement
$0.2 < \kappa \leq 0.4$	Fair agreement
$0.4 < \kappa \leq 0.6$	Moderate agreement
$0.6 < \kappa \leq 0.8$	Substantial agreement
$0.8 < \kappa \leq 1$	Almost perfect agreement

2.2. Reaching and assessing consensus

Consensus was developed throughout the three rounds of the Delphi study.

For selection items, consensus was assumed to be reached if 75% of the experts gave the same response, which is in accordance with the threshold used in [31,32]. Reviews analyzing the Delphi method itself considering a multitude of previous studies show that values between 51% and 95% are common as consensus thresholds [34] and report a median threshold of 75% of agreement percentage [35]. Another methodical study [36] also suggests to use agreement percentages to track the evolution of consensus while it recommends to demonstrate consensus stability by a trend of increasing inter-rater agreement via Kappa statistics. The free-marginal Kappa κ_{free} is suited to assess agreement studies and thus selected to assess inter-rater agreement. Generally, $\kappa_{free} = 0$ shows that the agreement could just be due to chance while $-1 \geq \kappa_{free} < 0$ indicates even worse agreement and $0 < \kappa_{free} \leq 1$ points towards real agreement. Yet, certain levels of agreement are distinguished as given in Tab. 1, which is considered in the interpretation of the results.

Selection items that allowed multiple choices were explored in the first round and some were slightly reformulated for the second round. Response options that were selected by less than 25% of experts in the second round were removed from the multiple choices in the third round. The response possibilities were designed to cover as much technical solutions as possible to explore the solution space exhaustively. To this end, all selection items allowing for multiple choices also included the option "other", which could be used by the experts to suggest alternative solutions. Free text items were evaluated qualitatively by the authors and identified patterns were coined into selection items for the subsequent round.

2.3. Procedure

The three rounds of the Delphi study were implemented by three consecutive online questionnaires using software and servers of Rogator AG, Nuremberg, Germany. The questionnaires ask for practical experience of the experts.

2.3.1. Delphi round 1

After surveying the experts' professional backgrounds and email contacts, the following text was presented to give them an introduction to the topic and the corresponding design requirements based on [10]:

> *Understanding the integration of wearable robotic devices such as prosthetic hands in the body schema of their human users has a distinct potential to improve human-robot*

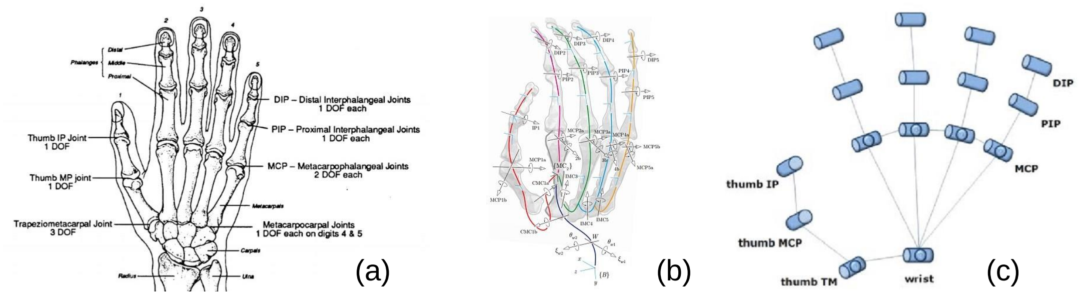

Figure 1. Common representations and models of human hand kinematics by Sturman [37] (a) and robotic implementations by Gabiccini et al. [38] (b) and Cerulo et al. [39] (c), which were presented in the questionnaire, without any claim of exhaustiveness.

interaction. Beyond this, such insights could improve human-robot interaction in other domains, e.g., industrial robotics. In return, robotic devices can help to investigate the psychological fundamentals of body schema integration. Such experiments investigate how artificial limbs are be experienced as a part of a participants body. Therefore, the real human hand is hidden and the artificial one imitates its motions.

According to previous hardware requirement analyses (Beckerle et al., 2016), the occurrence and quality of integration relies on hiding the real limb, anatomical plausibility (i.e., robotic hand motion/position/orientation), similar visual appearance of robotic and human hand, and technically-caused delays. Target applications are usually putting rather low mechanical load on the hand, e.g., grasping balls or handling empty bottles. However, for good motion imitation, fast reactions of the robotic hand are required. Costs should be kept low.

For further information, you might consider Beckerle et al., 2016:
http://ieeexplore.ieee.org/abstract/document/7745205/

The experts were asked to answer the questionnaire given in Tab. 2 to determine appropriate actuation, sensing, and control approaches. Moreover, the experts were asked to indicate which joints of the human hand and wrist they would mechanically implement in a reduced kinematic structure. Therefore, kinematic models of the human hand from the literature were presented to the participants (see Fig. 1 for the models) and they were asked to specify their selections in a text box. Additionally, they were asked to specify if they would implement the selected joints with or without actuation or if they would prefer to couple some of the selected joints.

2.3.2. Delphi round 2

Items that reached consensus in the first round were omitted in the second and others were reformulated as shown in Tab. 3 and 4. Considering the suggestions regarding the kinematic design from the text box item of the first round, more specific selection items were designed and evaluated in the second round (see Tab. 4). To prepare the experts before they answered the second questionnaire, the results, the conclusions of the authors, and the redesign of the questionnaire were presented to them. Furthermore, they were informed about certain design requirements that seemed to be unclear:

Please note that omitting a finger is not an option since a human-like appearance seems crucial for embodiment research. The coupling of joints is a promising path to a simple design but might also affect functionality. Hence, please consider the questions critically to find a simple but functional design.

Table 2. Selection items and results of the questionnaire surveyed in the first Delphi round ($N_1 = 14$).

No.	Item (κ_{free})	Response possibilities	Agreement
A1	Would you prefer full or under-actuation of the fingers? ($\kappa_{free} = 0.473$)	Full actuation (i.e., an actuator per mechanical joint)	14.29%
		Underactuation (e.g., cable driven)	85.71%
A2	Would you suggest classic (rigid/stiff) or elastic/soft actuation of the fingers? ($\kappa_{free} = 0.473$)	Classic (rigid/stiff) actuation	14.29%
		Elastic/soft actuation	85.71%
A3	Which actuation principle would you suggest? ($\kappa_{free} = 0.284$)	DC motor	57.14%
		AC motor	0.00%
		Servo motor	28.57%
		Electromagnet	0.00%
		Pneumatics	7.14%
		Hydraulics	0.00%
		Piezoelectric	0.00%
		Other	7.14%
A4	Which quantities would you suggest to measure for control reasons? (multiple answers possible)	Finger position	35.71%
		Finger flexion	50.00%
		Hand position	35.71%
		Hand orientation	64.29%
		Fingertip contact forces/ torques	50.00%
		Palm contact forces	21.43%
		Actuator position	35.71%
		Actuator velocity	14.29%
		Actuators forces/torques	57.14%
		Actuator currents	28.57%
		Pressure	21.43%
		Other	0.00%
A5	Which control strategy would you suggest? ($\kappa_{free} = 0.077$)	Feedforward control	28.57%
		Feedback control	57.14%
		Other	14.29%
A6	Which quantity/property would you select to be controlled? (multiple answers possible)	Position	57.14%
		Velocity	57.14%
		Force/torque	92.86%
		Impedance	42.86%
		Other	0.00%

The note that omitting a finger should not be considered an option was made since anatomical soundness is essential to elicit embodiment in terms of the rubber hand illusion [6] and human-likeness generally influences robot acceptance [40].

2.3.3. Delphi round 3

The questionnaire resulting from the evaluation of the second round is presented in Tab. 5 and Tab. 6. From the responses regarding the kinematics, a first sketch of the kinematic structure was prepared and presented to the experts. It is shown in Fig. 2 and outlines how joints should be implemented (blue) or if consensus was missing (red) as well as which joints should be coupled (orange). This kinematic structure and the statistic results of the second round were given to the experts to prepare the final round.

Furthermore, they were informed about certain design requirements that seemed to be unclear. Regarding the control quantity item it was noted:

> *The picture got clearer here and it might be useful to integrate more than one sensor. Hence, this questions reappears in this round and we remove all options that received less than 25%. Hand position and orientation are to be combined since they could be jointly sensed by an inertial measurement unit (IMU). Actuator forces/torques and currents are also combined since they might be calculated from each other.*

Moreover, the question surveying the kinematic structure and actuation of the four fingers was adapted to ask if actuation with a single motor would make sense:

> *Due to a comment of one expert, we will also ask if all four fingers could use a single motor for their DIP, PIP, and MCP joints.*

3. Results

This section describes the progress of finding consensus, the resulting design decisions, and the final hand concept. The expert opinions after each Delphi round are presented in Tab. 2, Tab. 3, Tab. 4, Tab. 5, and Tab. 6.

3.1. Delphi round 1

In the first round, the experts reached clear consensus to design an under-actuated system with elastic actuation, which was both preferred by 85.71% each. This is underlined by $\kappa_{free} = 0.473$ indicating moderate agreement. Regarding the underlying actuation principle, the majority of experts voted for using DC motors (57.14%) or servo motors (28.57%). Pneumatics and other solutions were only preferred by a single expert each and thus omitted like all other possible options, which were not selected at all. Generally, the ratings only achieved fair agreement ($\kappa_{free} = 0.284$). The possible item response were limited to DC and servo motor in the second round.

Regarding the quantities suggested to be measured for control, the experts' responses covered a rather wide range. Hence, the question was identically moved to the second round to get a clearer result that considers the other design decisions. As promising control strategies, many of the experts preferred feedback (57.14%) over feedforward (28.57%) and other methods (14.29%), but $\kappa_{free} = 0.077$ indicates poor agreement. Since mixtures of feedback and feedforward were often specified as the "other" option and to tackle the poor agreement, the question was repeated in the second round and ”other” was replaced by ”combined feedforward and feeback control”. Since the expert responses regarding the quantity/property to be controlled were rather distributed, this item was also repeated in the second round.

3.2. Delphi round 2

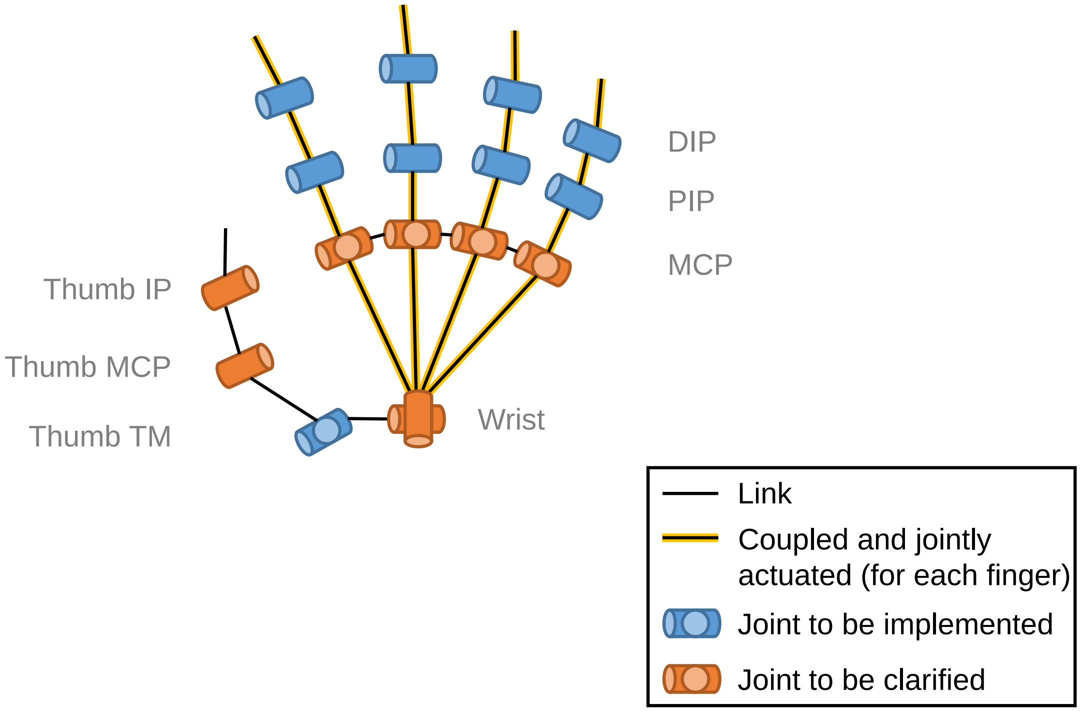

Figure 2. Kinematic structure determined from the results of the second round ($N_2 = 12$).

In the second round, the expert opinions about the actuation principle remained similar ($\kappa_{free} = -0.061$; agreement might be due to chance). Both options, DC motor (58.33%) and servo motor (41.67%), were thus surveyed again in the final round.

The selection of the quantities suggested to be measured for control got slightly clearer since palm contact forces, actuator velocities, and pressure were selected by a single expert each. Since this result is clearly below the 25% threshold and similar to the one from the first round, all three options were omitted in the final round. Moreover, actuator forces/torques (66.67%) and actuator currents (16.67%) were combined in a single response option since one might be calculated from the other (see Sect. 2.3.3). The responses asking for the quantity/property to be controlled all surpassed the 25% threshold. Thus, the item was identically moved to the third round. Regarding the control strategy, the experts agreed that pure feedforward is not an option (0.00%), while some preferred pure feedback (41.67%) and others suggested combined feedforward and feeback (58.33%). Due to this fair agreement ($\kappa_{free} = 0.205$), the item was asked again in the final round for a robust result that considers the final design.

The selection items regarding the kinematic structure that were extracted from the text box item in the first round reached rather clear results in the second: the experts

Table 3. Actuation- and control-related selection items and results of the questionnaire surveyed in the second Delphi round ($N_2 = 12$).

No.	Item	Response possibilities	Agreement
B1	Which actuation principle would you suggest? ($\kappa_{free} = -0.061$)	DC motor	58.33%
		Servo motor	41.67%
B2	Which quantities would you suggest to measure for control of the joints (multiple answers possible, control of the device by the human operator is excluded)	Finger position	58.33%
		Finger flexion	25.00%
		Hand position	25.00%
		Hand orientation	50.00%
		Fingertip contact forces/ torques	33.33%
		Palm contact forces	8.33%
		Actuator position	33.33%
		Actuator velocity	8.33%
		Actuators forces/torques	66.67%
		Actuator currents	16.67%
		Pressure	8.33%
		Other	0.00%
B3	Which quantity/property would you select to be controlled? (multiple answers possible)	Position	50.00%
		Velocity	33.33%
		Force/torque	75.00%
		Impedance	33.33%
		Other	0.00%
B4	Which control strategy would you suggest? ($\kappa_{free} = 0.205$)	Feedforward control	0.00%
		Feedback control	41.67%
		Combined feedforward and feedback control	58.33%

Table 4. Kinematics-related selection items and results of the questionnaire surveyed in the second Delphi round ($N_2 = 12$).

No.	Item	Response possibilities	Agreement
B5	Should DIP and PIP joints of the four fingers be coupled kinematically and jointly actuated? ($\kappa_{free} = 0.667$)	Yes No	91.67% 8.33%
B6	Should DIP, PIP, and MCP joints of the four fingers be coupled kinematically and jointly actuated? ($\kappa_{free} = 0.182$)	Yes No	75.00% 25.00%
B7	Should MCP adduction of the four fingers be omitted? ($\kappa_{free} = -0.061$)	Yes No	58.33% 41.67%
B8	Should the IP and MCP joints of the thumb be coupled kinematically and jointly actuated? ($\kappa_{free} = 0.030$)	Yes No	66.67% 33.33%
B9	Which TM joints of the thumb should be implemented and be controllable? ($\kappa_{free} = 0.596$)	TM flexion/extension TM adduction/abduction both none	16.67% 0.00% 83.33% 0.00%
B10	Which wrist joints should be implemented and be controllable? ($\kappa_{free} = 0.253$)	Wrist flexion/extension Wrist pronation/supination both none	16.67% 8.33% 66.67% 8.33%
B11	Should the adduction/abduction of the finger joints be coordinated with flexion/extension by control? ($\kappa_{free} = -0.091$)	Yes No	50.00% 50.00%
B12	Should the control of wrist joint movements be coupled with hand opening/closing? ($\kappa_{free} = 0.667$)	Yes No	8.33% 91.67%

agreed that the DIP and PIP joints (91.67%, $\kappa_{free} = 0.667$; substantial agreement) as well as the MCP joints (75%, $\kappa_{free} = 0.182$; poor agreement) of each of the four fingers should be coupled kinematically and jointly actuated. While a trend towards omitting MCP adduction of the four fingers is observed (58.33%), the agreement could be due to chance ($\kappa_{free} = -0.061$). Similarly, experts tended to kinematically couple and jointly actuate the IP and MCP joints of the thumb (66.67%) with potentially random agreement ($\kappa_{free} = 0.030$). Due to this, both items were moved to the third round. Consensus was made regarding the implementation of the TM joints of the thumb, which are suggested to both be mechanically implemented and controllable by an actuator (83.33%, $\kappa_{free} = 0.596$; moderate agreement). Regarding the wrist joints, most experts preferred to implement and control both, wrist flexion/extension and wrist pronation/supination (66.67%). Since this did not satisfy the consensus criterion of 75% and only fair agreement $\kappa_{free} = 0.253$, the item reappeared in the third round to get an updated result considering the corresponding design iteration.

The two last items related to kinematics surveyed software-based solutions. The expert opinions with respect to the question if adduction/abduction of the finger joints should be coordinated with flexion/extension by control was ambivalent (50% vs. 50%, $\kappa_{free} = -0.091$; agreement might be due to chance). Yet, the experts clearly agreed to not couple the control of wrist joint movements with hand opening/closing (91.67%, $\kappa_{free} = 0.667$; substantial agreement). Hence, the former item was asked again in the final round, while the latter was omitted.

The sketch presented in Fig. 2 represents the resulting intermediate kinematic structure after the second Delphi round.

3.3. Delphi round 3

In round three, the experts did not agree on the actuation principle ($\kappa_{free} = 0.077$; poor agreement). Due to this, the selection of either a DC motor (69.23%) or a servo motor (30.77%) remains an open design variable after this study.

The picture regarding the quantities measured for control got distinctly clearer since finger position, hand position and orientation, fingertip contact forces/torques, and actuator forces/torques (and currents) were all selected by (61.54%) of the experts. Hence, they should be preferred over measuring finger flexion (23.08%) and appear more important than actuator position (30.77%). The experts agreed to select force/torque (76.92%) as a control quantity. A trend towards additionally considering position (53.85%) is observed, while velocity and impedance are omitted with (23.08%) each. Consensus to combine feedforward and feedback control was achieved (84.62%, $\kappa_{free} = 0.577$; moderate agreement).

Regarding the kinematic structure, a tendency towards actuating the DIP, PIP, and MCP joints of the four fingers by a single motor is observed but no consensus is made (69.23%, $\kappa_{free} = 0.077$; poor agreement). It thus remains a design option, that might be considered for simplicity or omitted for flexibility. In contrast to the second round, the experts agreed to omit MCP adduction of the four fingers (76.92%, $\kappa_{free} = 0.231$; fair agreement) and to kinematically couple and jointly actuate the IP and MCP joints of the thumb (92.31%, $\kappa_{free} = 0.692$; substantial agreement). Due to the poor agreement ($\kappa_{free} = 0.197$), the implementation and control of the wrist joints remains an open design issue with two possible solutions, i.e., only wrist flexion/extension (38.46%) or in combination with wrist pronation/supination (53.85%).

Contrary to the second round, the expert opinions show a tendency towards not

Table 5. Actuation- and control-related selection items and results of the questionnaire surveyed in the third Delphi round ($N_3 = 13$).

No.	Item (Kappa)	Response possibilities	Agreement
C1	Which actuation principle would you suggest? ($\kappa_{free} = 0.077$)	DC motor	69.23%
		Servo motor	30.77%
C2	Which quantities would you suggest to measure for control of the joints (multiple answers possible, control of the device by the human operator is excluded)	Finger position	61.54%
		Finger flexion	23.08%
		Hand position and orientation	61.54%
		Fingertip contact forces/torques	61.54%
		Actuator position	30.77%
		Actuators forces/torques (or currents)	61.54%
C3	Which quantity/property would you select to be controlled? (multiple answers possible)	Position	53.85%
		Velocity	23.08%
		Force/torque	76.92%
		Impedance	23.08%
C4	Which control strategy would you suggest? ($\kappa_{free} = 0.577$)	Feedforward control	0.00%
		Feedback control	15.38%
		Combined feedforward and feedback control	84.62%

Table 6. Kinematics-related selection items and results of the questionnaire surveyed in the third Delphi round ($N_3 = 13$).

No.	Item	Response possibilities	Agreement
C5	Should DIP, PIP, and MCP joints of the four fingers be actuated by a single motor? ($\kappa_{free} = 0.077$)	Yes No	69.23% 30.77%
C6	Should MCP adduction of the four fingers be omitted? ($\kappa_{free} = 0.231$)	Yes No	76.92% 23.08%
C7	Should the IP and MCP joints of the thumb be coupled kinematically and jointly actuated? ($\kappa_{free} = 0.692$)	Yes No	92.31% 7.69%
C8	Which wrist joints should be implemented and be controllable? ($\kappa_{free} = 0.197$)	Wrist flexion/extension Wrist pronation/supination both none	38.46% 7.69% 53.85% 0.00%
C9	Should the adduction/abduction of the finger joints be coordinated with flexion/extension by control? ($\kappa_{free} = -0.026$)	Yes No	38.46% 61.54%

coordinating adduction/abduction of the finger joints with flexion/extension by control (61.54%), but confirmation is missing ($\kappa_{free} = -0.026$; agreement might be due to chance).

3.4. Final design concept

A sketch of the final design concept after the three Delphi rounds is presented in Fig. 3. The DIP, PIP, and MCP joints of each of the four fingers as well as the IP and MCP joint of the thumb are kinematically coupled and jointly actuated (orange lines). Moreover, these joints are all implemented with a single degree-of-freedom (DoF), i.e., flexion/extension. The thumb TM joint is implemented with two DoFs. The selection between a one- or two-DoF joint is open for the wrist but experts tended to implement both DoFs.

Hence, three actuators are required for thumb and up to two for the wrist. Each of the four fingers is actuated by one actuator. Yet, the option to actuate all four fingers with a single acutator remains for simple grasping tasks. These six to nine actuators can be selected to be either based on a DC or a servo motor. In any case, elastic actuation concepts are to be preferred.

With respect to control, a combination of feedforward and feedback techniques are suggested to control force/torque. Moreover, position might be added as a control quantity. Finger position, hand position and orientation, fingertip contact forces/torques, and actuator forces/torques (and currents) were selected to be measured for control reasons. Hence, the corresponding sensors are suggested to be implemented, e.g., joint encoders, IMUs, or force/torque transducers.

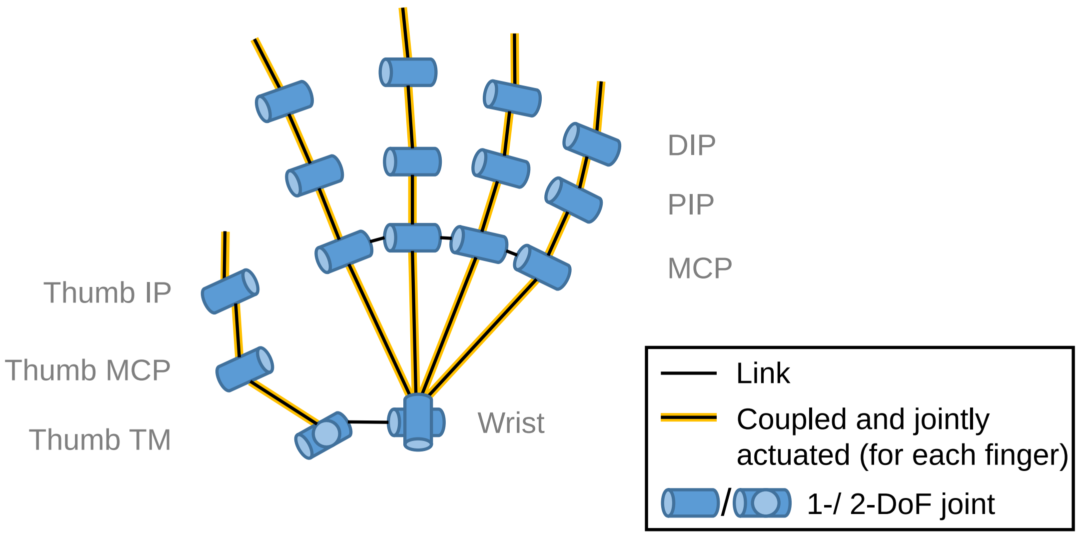

Figure 3. Final design concept after the three Delphi rounds ($N_1 = 14$, $N_2 = 12$, $N_3 = 13$).

4. Discussion

The robotic hand concept developed in this paper strongly relies on the concepts of soft actuation, underactuation, and synergistic actuator organization. As mentioned above, synergies are an established concept in robotic community. By coupling joints and adding compliance, kinematic and control complexity can be reduced while still guaranteeing appropriate dexterity and robustness.

The experts suggest a certain level of dexterity to achieve embodiment of the robotic hand, which significantly influences the kinematic design and goes far beyond the capabilities of existing hand designs for the exploration of human body experience [10]. The results on the question if and how the four fingers and their joints should be coupled and jointly actuated yields consensus to actuate all joints of each particular finger by one motor. However, they did not agree to introduce another simplification that would actuate all four fingers by a single motor. As the investigation of embodiment is a key design criterion, the experts seem to deem single digit movement as crucial, which is in line with previous approaches [10]. Yet, the solution to actuate all four fingers jointly could be an option to reduce technical complexity for applications that are limited to simple grasping tasks. While one main objective of the hand design is improving reaction times, the finger kinematics could be designed to adapt to different loading scenarios, e.g., by the mechanism implemented in [33]. With two actuated metacarpal joints and coupled flexion of the IP/MCP joints, the thumb design is rather complex. While integrating two independently operated degrees of freedom at the thumb basis appears to be non-standard and might cause difficult engineering challenges, the study showed a clear consensus of the experts. This remarks the importance of the thumb motion and opposition to perform dexterous manipulation, which is in line with the demand of good manipulation capabilities stated above and a clear novelty compared to previous solutions [10]. The experts further agreed to implement both one or two joints; similar to the concept from [41]. The overall kinematic design indicates potential benefits of developing more dextrous hands than the Pisa/IIT SoftHand or commercial prostheses such as the Michelangelo hand by Otto Bock. Besides assessing the agreement percentage, the derived design decisions are ensured by κ-statistics, which mostly indicate moderate to substantial agreement. Yet, it has to be noted that the results to omit MCP adduction of the four fingers (fair agreement) and to couple their DIP/PIP with their MCP joints (poor agreement) are not finally confirmed.

Regarding the actuation principle to be used, experts clearly prefer standard solutions, i.e., DC and servo motors. While this agrees with previous solutions [10], the selection of appropriate sensor appear to be more complex. Relevant quantities for controls and haptic feedback are finger position, hand position and orientation as well as fingertip contact forces/torques and actuator forces/torques. To reduce the number of considered quantities and simplify their interpretation, sensory synergies that connect low-level sensory variables with high-level human percepts might be considered [1,17]. Due to clear expert consensus, the sensory data should be used for combined feedforward and feedback control of force and/or torque. Additionally, position might be added as a control quantity in a hybrid control approach. Realizing soft actuation and such combined and hybrid controls could be the new frontiers for soft robotic hands [42].

While enabling quantitative evaluation, the study design based on questionnaires could constrain the broadness of potential replies. This is mitigated in the presented study by providing other options and free text items to comply with the explorative research question. Another potential limitation is that only experts working in western countries participated. While this might bias the design concept towards use by Westerners, similarities to an eastern design are observed [41]. Yet, the influence of cultural backgrounds on human body experience and sensory-motor skills is very relevant and might be considered in the future.

In conclusion, the design suggested by the results of the expert study is clearly driven by the concept of synergies and reaching certain manipulation capabilities. While the former simplifies the mechatronic design, the latter can result in more complex kinematics and actuation. Moreover, non-standard results such as the 3-DoF thumb represent design and realization challenges, but might be worth the effort considering user experience, especially in terms of embodiment. The realization of a working prototype including haptic feedback is intended as a future work.

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Disclosure statement

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Notes on contributor(s)

P. Beckerle coordinated the writing process and the expert study. M. Bianchi, G. Salvietti, and C. Castellini contributed equally to participant acquisition, study design, evaluation, and paper preparation.

5. References

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