Hand Kinematics Characterization While Performing Activities of Daily Living Through Kinematics Reduction

Néstor J. Jarque-Bou, Margarita Vergara, Joaquín L. Sancho-Bru, *Member, IEEE*, Verónica Gracia-Ibáñez, and Alba Roda-Sales

***Abstract*—Improving the understanding of hand kinematics during the performance of activities of daily living may help improve the control of hand prostheses and hand function assessment. This work identifies sparse synergies (each degree of freedom is present mainly in only one synergy), representative of the global population, with emphasis in unveiling the coordination of joints with small range of motion (palmar arching and fingers abduction). The study is the most complete study described in the literature till now, involving 22 healthy subjects and 26 representative day-to-day life activities. Principal component analysis was used to reduce the original 16 angles recorded with an instrumented glove. Five synergies explained 75% of total variance: *closeness* (coordinated flexion and abduction of metacarpophalangeal finger joints), *digit arching* (flexion of proximal interphalangeal joints), *palmar-thumb coordination* (coordination of palmar arching and thumb carpometacarpal flexion), *thumb opposition*, and *thumb arch*. The temporal evolution of these synergies is provided during reaching per intended grasp and during manipulation per specific task, which could be used as normative patterns for the global population. Reaching has been observed to require the modulation of *closeness*, *digit arch* and *thumb opposition* synergies, with different control patterns per grasp. All the synergies are very important during manipulation and need to be modulated for all the tasks. Finally, groups of tasks with similar kinematic requirements in terms of synergies have been identified, which could benefit the selection of tasks for rehabilitation and hand function assessments.**

***Index Terms*—Activities of daily living, hand grasps, hand kinematics, manipulation, principal component analysis, reaching, synergies, temporal evolution.**

I. Introduction

THE hand is a complex mechanical system that provides humans with the ability to reach, grasp, and manipulate objects, which are essential to perform activities of daily living (ADL). Reaching precedes grasp and combines the approaching movement of the hand to the object and the finger joint motion in anticipation of the intended grasp [1], [2]. Reaching ends when the hand grasps and stably holds the object. A different grasp is used depending on the ability, force and dexterity required to perform the task, thus the number of grasps of the taxonomies reported in the literature is different depending on their purpose [3]–[5]. Subsequent manipulation is characterised by hand motions that allow the required movements of an object to perform activities. Manipulation can be as simple as moving an object or as complex as simultaneously transporting and handling an object accurately with fingertips [6]. Consequently, the ability to reach, grasp and manipulate an object involves many neural structures that work in concert in a highly complex way to control intricate hand kinematics [7].

The study of hand kinematics required to perform ADL in both phases can provide objective data to better understand human movement (e.g. to assess hand function [8]), improve grasping in robotics [9], make hand models more realistic (such as three-dimensional modelling for films or computer games [10]), or even improve rehabilitation and physiotherapy [11]–[13]. However, the high number of degrees of freedom (DoF) of the hand hinders such analysis, so that the studies of the kinematics used during ADL are mainly limited to the analysis of the ranges of motion of the hand joints [14], [15] and grasping trajectories and velocities [16], [17]. Other important kinematic characteristics, such as the coordination underlying ADL performance [18], are not addressed.

In a previous work [19], we proposed kinematic reduction through principal component analysis (PCA) to make the analysis of the simultaneous movement of all hand joints affordable, as all these movements are coordinated because of mechanical and neurological couplings [18], [20]. As a result, we showed that using these coordinated movements to address hand characterisation is a good compromise between the simplicity of kinematic representation and accuracy. These coordinated movements are commonly known as kinematic synergies [21], and are suggested to represent the basic building blocks underlying natural hand motions that can be used to represent hand movements to, therefore, reduce the dimensionality of kinematics [22]–[24]. PCA has been previously applied

Manuscript received October 17, 2019; revised March 22, 2020; accepted May 26, 2020. Date of publication May 29, 2020; date of current version July 8, 2020. This work was supported in part by the Projects MCIU/AEI/FEDER, UE, under Grant PGC2018-095606-B-C21 and Grant UJI-B2017-51 and in part by the FPI under Grant BES-2015-072480.
(Corresponding author: Néstor J. Jarque-Bou.)

The authors are with the Department of Mechanical Engineering and Construction, Universitat Jaume I, 12071 Castellón, Spain (e-mail: jarque@uji.es; vergara@uji.es; sancho@uji.es; vgracia@uji.es; rodaa@uji.es).

This article has supplementary downloadable material available at http://ieeexplore.ieee.org, provided by the authors.

Digital Object Identifier 10.1109/TNSRE.2020.2998642

to study the human grasp for different purposes [19], [25]–[32], but these studies provide limited knowledge about the characterisation of hand kinematics while performing ADL. A recent study [33] intended to be representative of ADL performance as it used data on the hand while performing a wide range of grasps. However, data were limited to grasp performance and did not consider manipulation in real ADL. The main results of all these studies can be summarised as: a few synergies are needed to reproduce original movements; the more DoF considered, the more synergies required; synergies differ depending on the tasks or grasps considered; not all subjects use exactly the same synergies; hand actions are best represented as sparse combinations of a predefined set of basic synergies, with each involving a few DoF.

These studies present other limitations as regards representativeness. Firstly, the number of subjects considered in most works is quite limited (no more than 10), with no evidence of representativeness of the sample. Secondly, studies tend to focus on small sets of activities, which poorly represent the wide range of activities needed in daily living. Thirdly, studies do not consider important hand DoF such as the palmar arch, which is important both during reach-to-grasp [34] and object manipulation [35]. Fourthly, most works in the literature do not look for synergies sparse in DoF. Actually, some studies [23] suggest that the sparsity in DoF of synergies cannot be addressed by PCA methods because all DoF are used to compute any synergy. However, sparsity in DoF of synergies could be addressed by applying a rotation method trying to minimize the number of DoF in each synergy. Lastly, most studies focus on analysing either postural synergies of static grasps, and thus ignore the reaching and manipulation phases required to perform ADL, or very specific and controlled tasks. Regarding the first limitation, both the data sample size and the number of subjects involved in the study must be big enough to obtain representative results as the subject is expected to be the factor that explains most variance [19]. A selection of a limited set of representative tasks is needed given the wide variety of ADL humans can perform. This selection should consider specific protocols to standardise tasks [36] so as to help distinguish among different task phases [37]. However, defining such a set of representative ADL, susceptible to be standardised, is not straightforward. One possibility is to select tasks from those considered in the common clinical tests used to track the functional recovery of the upper extremity. These clinical tests consider a different variety of ADL, which ranges from 7 to 20. Some tests focus more on assessing fine motor skills, such as the Jamar Hand Function Test or the Jebsen Hand Function Test [38], while others centre more on measuring the ability to perform tasks required in ADL, such as the Sollerman Hand Function Test (SHFT) [39]. SHFT is one of the most popular tests that consists of performing 20 ADL at the maximum possible pace following an operator's instructions. It also includes whether subjects have to use both hands, or only the dominant one. SHFT is commonly accepted and used as a representative hand test while performing ADL, and is based on specific directed tasks, which makes these tasks easy to standardise. However, standard SHFT tasks do not consider some common grasps with a high percentage of use in ADL, such as the special pinch [5], therefore some extra activities should be added to make ADL more representative.

In this work, we used the kinematic reduction method presented previously [19] to characterise hand kinematics defined by 16 DoF (including palmar arch). We looked for synergies sparse in DoF, while 22 subjects performed a set of 26 representative simulated ADL based on SHFT. Data are presented by differentiating the reaching and manipulation phases to better understand human movement. During reaching, the approaching hand movement is determined by the position, orientation and shape of the object to be grasped, and also by the subject's characteristics, such as hand size and previous experience or preferences, which implies that subjects may use different types of grasps, even for the same ADL. On the contrary, during manipulation, hand motion is characterised by the required movements of the object to accomplish the task. Therefore, we present the results during reaching differentiating by the intended grasp performed by each subject during each ADL. The results during manipulation are presented by ADL.

II. Methodology

A. Experiment Description

The data used in this experiment come from the publicly available KIN-MUS UJI database [40]. This section briefly describes the experiment. For more details about the protocol, please refer to [40]. Twenty-two right-handed subjects gave their informed written consent before participating in this study, approved by our University's Ethics Committee. Subjects performed 26 simulated ADL (Table I), of which 20 were obtained from SHFT. Some ADL from SHFT were adapted to ensure their repeatability and to favour their standardisation. Six additional activities (A10, A15, A19, A24, A25, A26) were added based on the percentage of use of the commonest grasps used to perform ADL [5]. The scenarios with the objects used in the ADL are shown in the supplementary material (S1).

In order to help the ADL repeatability, each simulated ADL started and ended with the body and arms in the same posture (arms and hands relaxed at the side of the body when subjects were standing, or arms and hands resting in a relaxed position on the table when they were sitting). In addition, precise instructions for each task were provided, including details as the rotation angle of a key (A8), the position of a coin (A1 & A3), the rotation angle of a door handle (A9) or the amount of water to be poured (A21). The subjects could practice each task as many times as necessary in advance to become familiar with performing it before recordings. While carrying out each task, the operator marked (or labelled) the time stamp of two specific events: when any part of the hand came into contact with the object and when contact disappeared to release the object.

The right hand kinematics was recorded (100 Hz) while performing these simulated ADL with an instrumented glove (Cyberglove Systems LLC; San Jose, CA, USA) following a validated calibration protocol that includes some non-linear corrections to obtain anatomical angles [41]. The 16 recorded

TABLE I
DESCRIPTION OF THE ADL PERFORMED. WHEN NOT INDICATED, THE POSITION OF THE SUBJECT WAS STANDING

ADL	DESCRIPTION
A1	Collecting a coin and putting it into a change purse
A2	Opening and closing a zip
A3	Removing the coin from the change purse and leaving it on the table
A4	Catching and moving two different sized wooden cubes
A5	Lifting and moving an iron from one marked point to another
A6	Taking a screwdriver and turning a screw clockwise 360º with it
A7	Taking a nut and turning it until completely inserted inside the bolt
A8	Taking a key, placing it in a lock and turning it counter-clockwise 180º
A9	Turning a door handle 30º
A10	Tying a shoelace
A11	Unscrewing two lids and leaving them on the table
A12	Passing two buttons through their respective buttonhole using both hands
A13	Taking a bandage and putting it on his/her left arm up to the elbow
A14	Taking a knife with the right hand and a fork with the left hand and splitting a piece of clay (sitting)
A15	Taking a spoon with the right hand and using it 5 times to eat soup (sitting)
A16	Picking up a pen from the table, writing his/her name and putting the pen back on the table (sitting)
A17	Folding a piece of paper with both hands, placing it into an envelope and leaving it on the table (sitting)
A18	Taking a clip and putting it on the flap of the envelope (sitting)
A19	Writing with the keypad (sitting)
A20	Picking up the phone, placing it to his/her ear and hanging up the phone (sitting)
A21	Pouring 1L of water from a carton into a jug (sitting)
A22	Pouring water from the jug into the cup up to a marked point (sitting)
A23	Pouring the water from the cup back into the jug (sitting)
A24	Putting toothpaste on the toothbrush
A25	Using a spray over the table 5 times
A26	Cleaning the table with a cloth for 5 seconds

joint angles were: flexion of the metacarpophalangeal (MCP) joints of all fingers and thumb, interphalangeal (IP) joint of the thumb, and proximal interphalangeal (PIP) joints of the fingers; flexion and abduction of the thumb carpometacarpal (CMC) joint; relative abduction between fingers (index-middle; middle-ring; and ring-little); and palmar arch (P_Arch). A reference posture (hand resting flat on a table with fingers and thumbs close together, middle fingers aligned with forearms) was recorded before recording the hand kinematics while performing the selected ADL, and was considered zero for all the joint angles [41]. The recorded joint angles were filtered by a 2nd-order 2-way low-pass Butterworth filter with a cut-off frequency of 5 Hz and initial and final frames of each record during which the hands remained static were trimmed.

B. Data Analysis

The movement of each simulated ADL was divided into reaching and manipulation phases, defined by the marked events as follows:

• Reaching: until touching the object to be grasped.

• Manipulation: from touching the object until contact disappeared to release the object.

So that all subjects, ADL and phases weighted equally in the analyses, the number of frames of each record (per subject and each ADL) were resampled to 500 for each phase, with a total of 1000 frames per ADL and subject.

The following statistical analyses were performed:

Kinematic Reduction: In order to obtain representative kinematic synergies of global population, a PCA was applied to the data of all subjects altogether, including all the frames of both phases for all the ADL. The PCA matrix input was composed of an ensemble of 16 joint angle time-profiles (1000 frames) for the 26 ADL and 22 subjects (matrix dimension $16 \times 572{,}000$). Prior to computation of the PCs, the joint angles were normalised by rescaling them to unit variance in order to prevent the first PCs from reflecting the joint angles with the largest amplitudes [19]. The PCs with eigenvalues larger than 1 were obtained, and Varimax rotation applied. This is an orthogonal rotation method (factors obtained are uncorrelated) that provides more sparse synergies. When performing PCA, first factor of the unrotated solutions tends to be a general factor with almost every variable loading significantly, and accounting for a large amount of variance and the subsequent factors are then based on a residual amount of variance. Varimax rotation redistributes the variance from earlier factors to later ones, by maximising the sum of the variances of the squared loadings, so that all the coefficients will be either large or near zero [23]. PCs were interpreted from their correlations with the original variables, given by the rotated component matrix, and by the variance explained in the PCA. The synergy represented by each PC was interpreted (from the elements of the rotated PCs extracted) and graphically represented using Opensim. Finally, the temporal scores of PCs were calculated and used as reduced kinematic variables (RKV-PCs). Statistics (mean and SD) of the joint angles across all ADL and subjects (input matrix of the PCA) are also presented to properly interpret the values of the RKV-PCs, where a value of zero corresponds to the mean posture of the corresponding joints.

Minimum Sample Size: In order to study whether our sample size was big enough to be representative of ADL, we studied the instability of the PCA. We performed a Monte Carlo simulation to assess the degree of saturation of the variance explained when varying the number of subjects [42]. We performed an iterative approach that consisted of 21 steps. In each k-th step (k from 1 to 21), we considered a number of subjects N=k and performed 100 simulation runs with randomly selected samples of N subjects. I.e. we performed 2100 PCAs (21 steps $\times$ 100 simulations runs). For each PCA, we computed the amount of variance (of the original data, considering all subjects) that the resulting synergies explained. For each step, we averaged the results of variance explained across runs. Finally, we considered that the averaged variance explained got stabilised when the variation of the percentage of variance explained was smaller than 0.05 %.

Description of RKV-PCs During Reaching: The 9-type classification proposed by Vergara *et al.* [5] for the commonest grasps used in ADL was considered (Supplementary material, S2): Cylindrical grasp (Cyl), intermediate power-precision grasp (IntPP), lateral pinch (LatP), Hook grasp (Hook), lumbrical grasp (Lum), non-prehensile grasp (NonP), oblique palmar grasp (Obl), pad-to-pad pinch (PpP), and special pinch (SpP). This taxonomy was used to classify the intended grasp performed by each subject in each ADL through a visual check of the videos (22 subjects $\times$ 26 ADL = 572 videos).

Grasps were identified by looking at the time when the hand grasped the object for the first time, independently of the final

TABLE II
MEAN AND SD VALUES OF JOINT ANGLES ACROSS ADL, PHASE AND SUBJECTS. F/E: FLEXION/EXTENSION; AB/AD: ABDUCTION/ADDUCTION MOVEMENTS

Original variables			Statistics	
Digit	Joint	Movement	Mean (degrees)	SD (degrees)
Thumb	CMC	F/E	-2.51	18.33
	MCP	F/E	-3.86	9.45
	IP	F/E	0.82	17.70
Thumb-Index	CMC	Ab/Ad	13.32	4.75
Index	MCP	F/E	21.20	17.76
	PIP	F/E	39.32	21.39
Index-Middle	MCP	Ab/Ad	4.33	7.71
Middle	MCP	F/E	30.87	22.36
	PIP	F/E	43.05	20.13
Middle-Ring	MCP	Ab/Ad	6.37	5.86
Ring	MCP	F/E	21.55	21.88
	PIP	F/E	48.89	22.84
Ring-Little	MCP	Ab/Ad	1.12	5.05
Little	MCP	F/E	22.62	23.23
	PIP	F/E	41.03	22.22
Palm	P_Arch	F/E	28.47	15.00

grasp used for manipulation. The frequency of grasps observed per each ADL is presented, and the characterisation of the hand kinematics was made with a description of the RKV-PCs by differentiating per type of intended grasp:

• Mean values across subjects and frames of the RKV-PCs and differences between the 95th and 5th percentiles (range).

• Temporal description of the averaged RKV-PCs and 95 % confidence intervals (CI) across subjects.

Description of RKV-PCs During Manipulation: The characterisation of hand kinematics during manipulation was made by describing the RKV-PCs by differentiating per ADL by means of:

• Mean values across subjects and frames of the RKV-PCs and differences between the 95th and 5th percentiles (range)

• Temporal description of the averaged RKV-PCs and 95% CI across subjects.

A cluster analysis was performed by using the aforementioned statistics (mean and range values) to look for similar requirements while manipulating the different ADL. In this case, a hierarchical clustering analysis [43], with Euclidean distance taken as the distance criterion and Ward's method as the linkage criterion, was applied to group similar ADL. The resulting dendrogram with the ADL arranged in branches was used to identify the clusters by observing the distances in each step. The resulting groups of ADL were described, and a summary of their statistics of the RKV-PCs (and box plots) was used to characterise the kinematics during manipulation in each group of ADL. All the above analyses were performed using the MATLAB® software.

III. RESULTS

Table II shows the statistics of the postures recorded for each joint. Zero degrees correspond to the reference posture. Mean posture corresponds to a slightly flexed posture in all the joints, except for thumb joints CMC and MCP, with fingers and thumb also slightly abducted. All the joints seemed to have displayed ample variation during recordings, with Ab/Ad movements being those with less variation, as expected given their narrower range of motion.

TABLE III
CORRELATIONS OF THE PCS WITH THE ORIGINAL VARIABLES

Original variables			Estimated PCs				
Digit	Joint	Movement	PC_1	PC_2	PC_3	PC_4	PC_5
Thumb	CMC	F/E			**0.83**	0.25	-0.17
	MCP	F/E		-0.24	-0.24	-0.12	**-0.69**
	IP	F/E			-0.22		**0.75**
Thumb-Index	CMC	Ab/Ad	0.22			**0.86**	
Index	MCP	F/E	0.30	**0.78**		0.23	-0.18
	PIP	F/E	**0.66**	-0.25		0.11	0.20
Index-Middle	MCP	Ab/Ad		**-0.74**		0.32	
Middle	MCP	F/E	0.39	**0.81**		0.29	
	PIP	F/E	**0.94**			0.11	
Middle-Ring	MCP	Ab/Ad		**-0.74**	-0.21	0.34	
Ring	MCP	F/E	**0.50**	**0.76**		0.23	
	PIP	F/E	**0.95**				
Ring-Little	MCP	Ab/Ad	**-0.44**	**-0.46**		-0.10	-0.37
Little	MCP	F/E	**0.59**	**0.59**		0.26	0.20
	PIP	F/E	**0.88**	-0.17			
Palm	P_Arch	F/E			**-0.78**	0.28	-0.12
Explained variance (%)			25.6	22.9	9.2	8.8	8.5

A. Kinematics Reduction

Five PCs were extracted, which accounted for 75% of total variance, and the first two were responsible for 48% of this variance. Table III shows the rotated component matrix for the five PCs extracted, and shows the correlations between all the original variables and the estimated PCs. To simplify the interpretation of the results, values lower than 0.1 are not shown and those higher than 0.4 are shown in bold. Note that sparse synergies were observed as each DOF presents high values mainly only in one synergy, except the MCP movements of the ring and little finger which appear in the two first synergies. The five PCs extracted were graphically represented using Opensim and are shown in the supplementary material (S3).

PC1 shows a coordinated flexion of the PIP joints of fingers, with a slight MCP joint flexion of the fingers and a small abduction/adduction of the MCP of the little finger (i.e. *digit arch*). PC2 depicts coordinated flexion and adduction of the MCP joints of fingers (i.e. hand *closeness*). PC3 shows coordination between palmar arch extension and the CMC joint flexion of the thumb (i.e. *palmar-thumb coordination*). PC4 mostly depicts CMC thumb abduction (i.e. *thumb opposition*). PC5 shows coordination between the CMC extension and IP flexion of the thumb (i.e. *thumb arch*).

B. Minimum Sample Size

We found that at least 18 subjects were needed to have a variation in the averaged percentage of variance explained smaller than 0.05 %. The synergies obtained with 18 subjects explained an averaged variance of 74.78%, vs 75% when all the subjects were considered. And the resulting synergies with 18 subjects were similar to those obtained with all subjects, with angles between the vectors that represent both sets of synergies smaller than 10°.

C. Description of RKV-PCs During Reaching

Table T1 (Supplementary material) presents the frequency of the intended grasps performed by the subjects for each ADL

TABLE IV

MEAN AND RANGE (DIFFERENCE BETWEEN 95th PERCENTILE AND 5th PERCENTILE) OF EACH RKV-PC DURING REACHING PER EACH GRASP

	RKV-PC1		RKV-PC2		RKV-PC3		RKV-PC4		RKV-PC5	
	mean	range	mean	range	mean	range	mean	range	mean	range
PpP	-0.18	1.19	-0.23	1.16	-0.03	0.61	-0.09	1.07	-0.09	0.95
Cyl	-0.88	1.09	-0.47	1.40	0.10	0.76	0.07	1.81	0.25	0.80
Lum	-0.88	0.99	0.00	0.81	0.01	0.66	-0.15	1.66	-0.33	0.98
LatP	0.11	1.80	0.06	1.08	0.06	0.65	-0.48	0.82	0.08	0.97
Obl	0.73	2.60	-0.13	1.28	0.21	0.92	-0.71	1.20	-0.04	0.98
IntPP	0.24	2.00	-0.33	1.15	0.00	0.72	-0.46	0.98	0.08	0.86
Hook	0.13	1.41	-0.04	0.99	-0.20	0.46	-0.39	0.66	0.04	0.63
NonP	-1.08	0.61	-0.21	0.60	0.22	0.55	-0.63	0.77	0.02	0.47
All	-0.23	1.46	-0.17	1.06	0.05	0.67	-0.36	1.12	0.00	0.83

during reaching. PpP was the most frequent grip (35.1%) and Hook grasp was the least frequent (3.8%). In addition, SpP was not identified in the reaching phase in any case. Note that some ADL, e.g. #14 (using a knife and fork), #15 (eating soup with a spoon), #16 (writing with a pen) or #24 (putting toothpaste on a toothbrush), display no clear predominant grasp.

Table IV shows some statistics across subjects and frames of each RKV-PC per intended grasp, such as mean and range (difference between the 95th and 5th percentiles). Some differences per intended grasp can be observed. Across grasps, all the RKV-PCs present negative (less *digit arch*, *closeness* and *thumb opposition*) or zero mean values (*palmar-thumb coordination*, *thumb arch*). The widest range is observed for *digit arch*.

The temporal evolution of the mean value of each RKV-PC with the 95% confidence interval for the eight identified grasps is shown in the supplementary material (S4). Curve profiles are similar for some RKV-PC between different grasps (but with differences in the average and peak values), but present clear differences in other cases.

Digit arch (RKV-PC1) shows the highest positive mean and range values for the Obl grasp, with the highest negative values found for grasps NonP, Cyl and Lum. From the temporal evolution, *digit arch* presents similar profiles during the reaching movement for all grasp types (ascending value), i.e. when opening the hand required in the pre-shaping phase, the PIP joints are flexed. The Hook grasp presents the main difference, in which the ascending profile occurs at the end of the phase.

For all the grasps, *closeness* (RKV-PC2) shows almost no movement in the first half of the reaching phase; i.e. no movement is required for the MCP joints. The Cyl, Obl and Hook grasps firstly decrease in the second half of the movement, followed by an increase until the end of the phase; i.e. while opening the hand required in the pre-shaping phase for these grasps, MCP joints are first extended and then flexed. Contrarily, Lum and LatP showed only a slightly increase, which means only a slight flexion of the MCP joints, while PpP, IntPP and NonP need a slight decrease in the phase; i.e. these grasps require slightly extended MCP joints. Note that *closeness* shows the widest range value for the Cyl grasp.

Palmar-thumb coordination (RKV-PC3) profiles present some dispersion, but almost no differences during any grasps; i.e. with similar mean and range values between grasps, except

TABLE V

RKV-PC NEEDED TO BE CONTROL PER GRASP IN THE REACHING PHASE. THE MOVEMENT DIRECTION REQUIRED MARKED BY: + POSITIVE DIRECTION; − NEGATIVE DIRECTION. +/− BOTH DIRECTIONS NEEDED; = FIXED POSTURE WITHOUT MOVEMENT NEEDED

Grasp	RKV-PC1 (digit arch)	RKV-PC2 (closeness)	RKV-PC3 (palmar-thumb coordination)	RKV-PC4 (thumb opposition)	RKV-PC5 (thumb arch)
Cyl	+	+/-	=	+	=
PpP	+	-	=	+	=
Lum	=	=	=	+	-
LatP	+	+	=	+	=
IntPP	+	-	=	+	=
Obl	+	+	-*	+	=
Hook	+	+	=	=	=
NonP	=	=	=	=	=

*Little movement required.

for the Obl grasp that presents the widest range and mean values, needed to flex the palm to grasp the object while the thumb extends. It shows slight homogeneity between grasps (wide IC), except in PpP for which almost no changes can be seen.

Thumb opposition (RKV-PC4) has the highest negative mean and median value for NonP (less opposition of the thumb), while the highest positive mean and median and range values went for grasps Cyl and Lum (more opposition of the thumb). *Thumb opposition* profiles present a slight ascending value throughout movement for all grasps, except for the Hook grasp, which presents quite a constant value; i.e. in the reaching phase, thumb CMC abduction is required, except for the Hook grasp in which the CMC joint remains invariable.

Thumb arch (RKV-PC5) obtains the highest negative mean and median values for the Lum grasp (less arching of the thumb), while the highest positive values (more arching of the thumb) are for the Cyl grasp. *Thumb arch* profiles present visually similar and slightly increasing profiles for all the grasps, except for the Lum grasp, with a slightly lowering value throughout the reaching movement, i.e. for this grasp, coordination between CMC flexion and IP extension of the thumb is needed.

Table V summarises those synergies that need to be controlled per grasp in the reaching phase.

D. Description of RKV-PCs During Manipulation

Table VI shows some statistics of each RKV-PC per ADL across subjects and frames, such as the mean and difference between the 95th and 5th percentiles (range). The temporal evolution of the mean value of each RKV-PC per ADL, together with their 95% confidence interval, are shown in the supplementary material (S5).

Figure 1 shows the dendrogram from the hierarchical cluster analysis with the ADL organised on branches according to the similarity of their mean and range values of RKV-PCs. When the distance between the clustered groups in a step was high compared to the previous steps, the grouped elements or clusters are not so close, and is not considered appropriate. Six clusters or groups of ADL were identified. Table VII shows the description of these groups: ADL included in the group,

TABLE VI
MEAN AND RANGE (DIFFERENCE BETWEEN 95th AND 5th PERCENTILES) OF EACH RKV-PC DURING MANIPULATION FOR EACH ADL

	RKV-PC1		RKV-PC2		RKV-PC3		RKV-PC4		RKV-PC5	
ADL	mean	range	mean	range	mean	range	mean	range	mean	range
1	0.08	0.95	-0.18	1.08	0.26	0.67	0.99	1.09	-0.43	1.71
2	0.72	0.70	1.13	1.04	-0.04	0.48	-0.14	0.80	0.13	0.98
3	-0.47	1.86	0.55	1.88	0.27	1.61	0.02	2.62	-0.53	1.68
4	-0.33	1.24	-1.38	1.98	-0.33	0.90	0.61	1.31	1.01	1.94
5	0.61	0.48	1.19	0.96	-0.47	0.55	1.14	0.69	0.81	0.71
6	0.96	1.23	0.17	2.10	-0.62	1.19	0.00	2.02	0.01	1.23
7	0.01	1.11	0.80	1.88	-0.21	0.79	0.20	2.78	0.19	1.32
8	0.47	0.66	1.30	1.19	-0.04	0.66	0.06	1.32	0.24	1.37
9	1.33	1.22	0.65	1.39	-0.05	0.68	-0.50	0.64	0.55	1.32
10	0.59	1.82	0.13	1.90	0.28	1.15	0.28	1.96	-1.01	2.46
11	0.24	1.69	-2.31	3.04	-0.48	1.11	0.91	1.78	1.17	2.89
12	0.23	1.67	0.27	2.04	0.08	1.08	0.72	1.96	-0.73	1.82
13	0.91	1.92	0.11	1.80	0.07	1.08	-0.08	1.77	-1.06	2.72
14	1.17	1.04	0.15	1.31	-0.34	1.00	0.05	1.47	-0.31	1.54
15	0.81	1.08	0.93	1.69	-0.04	0.89	0.22	1.40	0.33	1.71
16	0.60	1.38	0.89	1.21	-0.37	1.13	0.72	1.71	1.50	2.33
17	-0.38	2.13	0.83	2.37	0.29	1.16	0.72	1.61	-0.75	1.89
18	0.12	2.32	0.27	2.07	0.41	1.08	0.74	1.87	-0.82	2.02
19	-0.39	0.91	-0.73	1.33	-0.18	0.66	-0.39	1.03	-0.43	0.80
20	1.24	1.18	-1.07	1.86	-0.41	1.16	-0.43	1.24	0.70	1.50
21	-0.24	0.48	-1.25	0.83	0.15	0.75	1.67	0.73	0.53	1.45
22	1.71	0.44	0.97	0.75	0.13	0.76	0.09	0.67	0.75	1.15
23	0.05	0.99	0.69	1.11	0.13	0.80	0.85	0.90	-1.64	1.56
24	0.58	1.61	0.74	2.08	0.39	1.18	0.25	1.72	-0.90	1.97
25	0.21	1.10	0.85	1.81	-0.36	0.96	-0.18	1.07	0.78	1.04
26	-0.86	0.81	-0.68	0.88	0.56	0.80	-1.38	0.99	0.01	0.85
All	0.38	1.23	0.19	1.60	-0.04	0.96	0.27	1.43	0.004	1.61

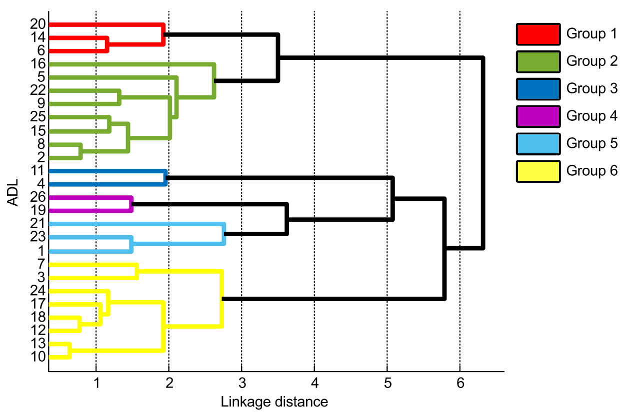

Fig. 1. Clusters obtained with the ADL organised on branches according to their similarity of the mean and range values of RKV-PCs.

intended grasps in the reaching phase, and average values across ADL of the mean and range of each RKV-PC.

The statistics of the mean and range values of each RKV-PC per group show clear differences for the identified groups. These values are represented in two box plots (Figure 2), one for the mean and another one for the range. Boxes represent median and percentiles (25% and 75%). Whiskers represent values that are within 1.5 times the interquartile range.

Some clear differences are observed between groups: Group 1 brings together activities #6, #14, and #20 (using a screwdriver, a knife and fork, picking up the phone).

TABLE VII
DESCRIPTION OF THE GROUPS OF ADL FROM THE CLUSTER ANALYSIS: ADLS GROUPED, GRASPS IN THE REACHING PHASE, AND THE AVERAGE VALUES OF THE MEAN AND RANGE OF EACH RKV-PC IN THE MANIPULATION PHASE

		Group1	Group2	Group3	Group4	Group5	Group6
# ADLs		6,14,20	2,5,8,9,15, 16,22,25	4,11	19,26	1,21,23	3,7,10,12, 13,17,18, 24
Intended grasps in reaching phase		*IntPP*	*LatP, Cyl, Hook, Obl*	*PpP*	*NonP*	*PpP, Cyl, Lum*	*Lum, PpP, NonP, LatP*
RKV-PC1	mean	1.126	0.807	-0.048	-0.629	-0.036	0.199
	range	1.151	0.883	1.462	0.862	0.807	1.805
RKV-PC2	mean	-0.251	0.987	-1.847	-0.706	-0.275	0.465
	range	1.755	1.255	2.514	1.107	1.005	2.001
RKV-PC3	mean	-0.457	-0.157	-0.406	0.192	0.182	0.197
	range	1.103	0.766	1.007	0.733	0.741	1.143
RKV-PC4	mean	-0.127	0.176	0.759	-0.888	1.17	0.356
	range	1.575	1.038	1.545	1.011	0.907	2.036
RKV-PC5	mean	0.133	0.636	1.089	-0.206	-0.515	-0.702
	range	1.422	1.326	2.418	0.822	1.574	1.986

This group has the highest positive mean value for *digit arch* (i.e. more digit flexion is needed), while the highest negative mean value is shown for *palmar-thumb coordination* (i.e. more palmar arch and thumb CMC extension is needed). *Closeness* and *thumb opposition* present the widest range of values.

Group 2 includes activities #2, #5, #8, #9, #15, #16, #22 and #25 (using a zip, moving an iron, opening a lock with a key, turning a door handle, eating with a spoon, writing with a pen, pouring water from a jug and using a spray). This group has the highest positive mean value for *digit arch* and *closeness* (i.e. more digit and MCP flexion are needed, with similar values).

Group 3 includes activities #4 and #11 (moving wooden cubes and unscrewing lids with a hand). This group has high positive values for *thumb opposition* and *thumb arch*, while the highest negative value is shown for *closeness* (i.e. more thumb opposition and arch are needed but with less hand closeness). This group also presents the widest range of values for *closeness* and *thumb arch*.

Group 4 comprises activities #19 and #26 (writing using a keypad and cleaning the table with a cloth). This group has almost all the RKV-PC with negative mean values, and the highest goes to *thumb opposition*.

Group 5 combines activities #1, #21, and #23 (putting a coin into a change purse, pouring water from a jug and from a glass). This group has the highest positive mean value for *thumb opposition*, while the highest negative mean value is shown for *thumb arch* (i.e. more thumb opposition and less thumb arch are needed). The range values are narrow for all the RKV-PCs, except for *thumb arch*.

Finally, Group 6 includes activities #3, #7, #10, #12, #13, #17, #18, and #24 (removing a coin from the change purse, inserting a nut inside a bolt, tying a shoelace, passing buttons, putting a bandage on the arm, folding a piece of paper and placing it inside an envelope, using a clip, and putting toothpaste on a toothbrush). This group presents similar

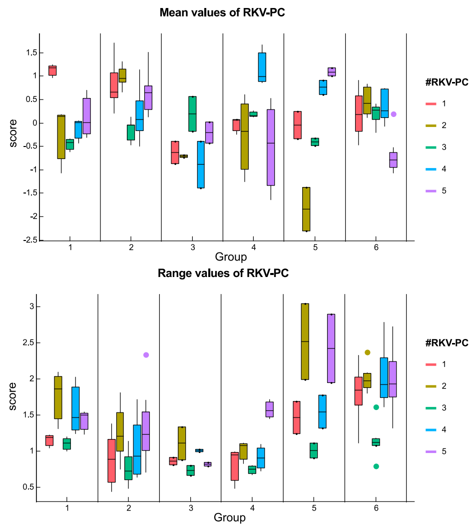

Fig. 2. Box plots of the statistics shown in Table VII (mean and range values of RKV-PCs after differentiating per group obtained in the dendrogram). Boxes represent median and percentiles (25% and 75%). Whiskers represent values that are within 1.5 times the interquartile range.

values for all the RKV-PCs, except for *thumb arch* with a high negative value (i.e. less arching of the thumb). Note that Groups 5 and 6 have the widest range values for all the RKV-PCs.

IV. Discussion

In this work we characterised the functional kinematics patterns of the hand while simulating ADL. We have yield synergies representative of global population, obtained from a high number of subjects (and we have proved that the number of subjects is high enough). We provide a detailed description of what are the most used synergies during the performance of representative ADL (being the most complete set of kinematic hand synergies related to ADL as far as we know), both during reaching (in terms of the grasps used) and during manipulation (in terms of specific tasks). The study was performed according to standardised actions based on SHFT, these tasks reflecting an accurate representativeness of hand functions in day-to-day life.

The PCA reduced the dataset size (16 DoF) to a limited number of kinematic patterns (5 PCs) underlying a wide variety of hand movements and explained most of the variability (over 75%) in the dataset. These results can be considered further experimental evidence for the modular organisation of the control strategy of the central nervous system, of the biomechanical connections between digits and of the functional organisation of multi-tendon finger muscles [18], [20]. The PCA extraction method herein used (Varimax rotation) allowed obtaining sparse synergies, i.e. each synergy uses a limited set of DoF (7 or less DOF) and actions are implemented with a combination of five synergies, according to the most recent findings [23]. Therefore, this set of new variables, each corresponding to a PC, provides almost the same information, but in a more easily interpretable manner: *digit arch, closeness, palmar-thumb coordination, thumb opposition,* and *thumb arch*.

The first two PCs (*digit arch* and *closeness*) explain almost 50% of variance, whereas all three remaining PCs explain only about 8%-9% each. As proposed by Santello [30], lower-order synergies (*digit arch* and *closeness*) define the gross motion of the hand, while higher-order synergies (*palmar-thumb coordination*, *thumb opposition* and *thumb arch*) are required to improve or refine the control of hands by finely adapting to the shape of an object and the task to be performed.

Some of the synergies herein obtained were similar to those found in a previous work for static postures [19] (*digit arch*, *closeness* and *palmar-thumb coordination*), and also to those reported in the literature [26], [28], [30], [33], especially the first two synergies (*digit arch* and *closeness*). However, the third synergy (*palmar-thumb coordination*) has not been previously described, as P_Arch DoF has a narrow range of motion (so that it is neglected without normalisation) and is not usually recorded. A recent study about grasping postures [33] reported a coordination of the palmar arching with wrist flexion, being the second synergy in percentage of explained variance. However, such coordination can't be considered as representative of ADL, as wrist motion is very dependent on the relative position between the product to be manipulated and the body [44], and such position was not varied in that study, but used the same location for all the grasps considered. The fourth and fifth synergies mainly represented thumb joint coordination, which is also frequently described in the literature [26]. However in the present study, the variance explained by these synergies was higher than that reported in most literature studies, save the recent study on grasping postures [33], which reported thumb opposition to be the third synergy. These results reveal the importance of the thumb for performing ADL. Thakur and collaborators [31] obtained more PCs than those reported herein because of the large number of objects (up to 50) and the extraction of subject-specific synergies. Della Santina and collaborators [45] studied the synergistic organization during environmental constraint exploitation on a plane, both in the pre-shaping and grasping phases. They found that, during unimpaired condition, only three PCs explained more than 72% of the variance, being the PCs similar to digit arch, and closeness, and being also similar between pre-shaping and grasping phases. However, palmar arch was not considered and the PCA methodology followed in those studies neglected the fingers abduction because of their smaller range of motion. In addition, as they did not applied rotation, the first unrotated factor was a general factor with almost every variable loading significantly, and accounting for a large amount of variance (>50%) and the subsequent factors are then based on the residual amount of variance. In our case, the rotation applied herein redistributed the variance from earlier factors to later ones to achieve sparse, simpler and more meaningful solutions.

To summarise, the methods used in our work present significant differences with respect the applied in most studies of literature: (i) In order to characterise the hand kinematics without hiding the importance of the palmar arch and other DoF with small range of motion (e.g., fingers abduction), joint angles were rescaled to unit variance (otherwise, the first PCs would reflect the joint angles with the largest amplitudes). (ii) We applied a Varimax rotation to the PCs, in order to obtain synergies sparse in DoF, according to most recent findings. (iii) Most studies have considered only static postures or simple movements, such as achieving a grasp, compared to the complex movements (including reaching and manipulation) considered herein.

Studying hand kinematics by the temporal evolution of the extracted synergies provided us with a good compromise between the simplicity of kinematic representation and accuracy. Some authors [31], [46], [47] have already considered the temporal evolution of the synergies. Averta and collaborators [47] warned that PCA cannot by applied to time series data of movement, since these data violate the assumption of being Independent and Identically Distributed. However, the violation does not affect the results when the objective is merely descriptive [48]. In this work, the PCA has been used mainly descriptively, although the results are also proposed as inference to the global population. This inference is possible because each of the ADLs can be considered as an independent observation (activities are quite different from each other), and because the complexity of the tasks, it is reasonable to consider more than one independent observation per ADL. We have considered 1000 frames per ADL, but it might have been enough a more reduced number of frames in each activity. However, given the complexity of the tasks, choosing the minimum number of frames to be representative was not straightforward.

The results obtained herein for the reaching phase are consistent with these previous studies, demonstrating synergistic variations of joint angles during pre-shaping [31]. However, temporal evolution of kinematic synergies during reaching have been poorly studied in previous works, among which stand a two-digit grasping study [49] that considered a very controlled environment, only the kinematics of two fingers (thumb and index fingers), and a limited number of grasps (Lateral and Pad-to-pad Pinch) and subjects (10). They found that reaching in both grasps could be explained by one PC (that accounted 76% of variance) representing the coordination between flexion of PIP and DIP index joints and thumb opposition (CMC and MCP abduction). This synergy was modulated to undertake the grasps, starting from a low score (index extended and CMC adducted) that increased reaching its maximum at object contact (index flexed and CMC abducted). Our outcomes are consistent with this result, showing similar temporal profiles for *digit arch* and *thumb opposition* in both Lateral Pinch and Pad-to-pad Pinch grasps during reaching (see supplementary material, S3).

Herein, the temporal evolution of RKV-PCs allowed us to identify the kinematic patterns required to shape the hand according to eight intended grasp types. The pad-to-pad pinch is achieved by controlling the *closeness*, *digit arch* and *thumb opposition* jointly (decreased *closeness* and increased *digit arch* and *thumb opposition*) to be able to open the hand in the pre-shaping phase. The cylindrical grasp is shaped by controlling the *digit arch* and *thumb opposition* jointly (both increase), and by also controlling *closeness* separately (a first decrease, followed by a posterior increase until the hand touches the object to be grasped). In this way, the hand controls the opening, depending on the object size. Lateral pinch, Intermediate power-precision grasp and oblique palmar grasp are characterised by the same profiles for almost all the RKV-PCs: they are achieved by jointly controlling the *digit arch* and *thumb opposition*, but *closeness* is controlled separately. Lateral pinch and oblique palmar grasp require them increasing at the end of the reaching phase to close the hand, while the intermediate power-precision grasp requires opening the hand in this phase. The lumbrical grasp is achieved mostly by controlling *thumb opposition* and *thumb arch*, i.e. controlling the thumb in the pre-shaping phase. The Hook grasp is shaped by controlling *closeness* and the *digit arch*, i.e. controlling digit movements in the pre-shaping phase. The non-prehensile grasp is characterised by almost no movement of any RKV-PC. Special pinch was not identified in any case during reaching, which is consistent with the fact that it is not used to pick up objects at first. They are grabbed with other grasp types like pad-to-pad pinch, and then grasp is changed during the manipulation (e.g. in tasks like writing).

These results could be used to improve the control of current prostheses during reaching by considering the different behaviours noted between the observed grasps. Table V summarises those synergies that need to be controlled per grasp, and shows that the most widely used synergies during reaching are *closeness*, *digit arch* and *thumb opposition* with different control patterns per grasp (Table V), while *thumb arch* and *palmar-thumb coordination* are almost fixed and, therefore, they do not need to be controlled, save *thumb arch* for the Lumbrical grasp. Note that *palmar-thumb coordination* is the same for all grasps (Table V), except for Oblique grasp, for which slight variation is observed in the mean posture to achieve this grasp. Although this variation could be greater if the observed object had other sizes/shapes, it would seem that its usefulness is better observed during manipulation.

We are not aware of any previous study on temporal evolution of kinematic synergies during the manipulation phase. Herein, we have addressed such study differentiating by ADL, as hand kinematics strongly depends on specific tasks: some tasks require more finger movements (e.g. fingers move while turning a nut), while others need to maintain an exact hand configuration (e.g. fingers are fixed when pouring water). In order to provide a global insight into the kinematics of this phase, we grouped the ADL with similar kinematic requirements, looking at mean postures and variability (mean and range between the 95th and 5th percentiles) of the RKV-PCs. The cluster analysis provided us with six groups of ADL:

Group 1 is defined by three ADL: using a screwdriver, using knife and fork and picking up the phone. These ADLs are characterised by using intermediate power-precision grasp to manipulate objects with an elongated shape. The hand kinematics of this group is characterised mostly by a positive *digit arch* and negative *palmar-thumb coordination*. In addition, *closeness* and *thumb opposition* present the widest ranges of movement. **Group 2** is defined by eight ADL: using a zip, moving an iron, opening a lock with a key, turning a door handle, eating with spoon, writing with a pen, pouring water from a jug and using a spray. These ADLs are characterised by a positive *digit arch* and *closeness*, corresponding to Cylindrical grasp, Oblique palmar grasp, Hook and Lateral Pinch. This group is composed of different ADL that need grasps for which the flexion of fingers is necessary. **Group 3** is defined by two ADL: moving wooden cubes and unscrewing lids with the hand. These ADL are characterised by a negative *closeness* and a positive *thumb arch* corresponding to Pad-to-pad Pinch. **Group 4** is defined by two ADL: writing using a keypad and cleaning the table with a cloth. These ADL are characterised by Non-Prehensile grasp. This group is characterised mostly by negative *digit arch, closeness* and *thumb opposition* with low ranges. **Group 5** is defined by three ADL: putting a coin into a change purse, pouring water from a jug and pouring water from a glass. These ADL are characterised by positive *thumb opposition*, corresponding to Cylindrical and Lumbrical grasps. This group is characterised mostly by positive *thumb opposition* and negative *closeness* and *thumb arch*, with wide ranges for *thumb arch*. Finally, **Group 6** is defined by eight diverse ADL: removing a coin from the change purse, inserting a nut inside a bolt, tying a shoelace, passing buttons through buttonholes, putting a bandage on an arm, folding a piece of paper and placing it into an envelope, using a clip, and putting toothpaste on a toothbrush. These ADL are more complex, and involve not only one grasp type and can, thus, be performed in more than one way. These ADL are characterised mainly by a negative *thumb arch* with wide ranges of motion for *digit arch*, *closeness*, *thumb opposition* and *thumb arch*.

The kinematic behaviour observed during manipulation differs from that during reaching. Comparison of use of RKV-PCs between phases was possible thanks to a PC extraction using the data of both phases altogether. Comparison of mean values between phases reveal that negative mean values are needed during reaching, i.e. less *digit arch*, *closeness* and *thumb opposition* (Table V), while positive mean values are required during manipulation, i.e. more *digit arch*, *closeness*, and *thumb opposition* (Table VII). *Palmar-thumb coordination* and *thumb arch* present similar mean values (about zero) in both phases, but with a wider range of movement during manipulation. During reaching, *thumb arch* and *palmar-thumb coordination* remain almost unchanged, while all synergies during manipulation need to be modulated for all tasks.

Finally, the results obtained may lead to some practical applications. The obtained groups of ADL are quite homogeneous in kinematic demands, so that rehabilitation procedures can benefit from them: assessing which is the affected movement, the action needed for rehabilitation can be planned. Furthermore, one representative ADL can be selected per group to consider quantitative parameters to evaluate hand kinematics, and to find different patterns that can simplify current rehabilitation protocols. The temporal evolution of reduced kinematic variables is provided for a wide range of healthy subjects during reaching (Supplementary material, S4) per intended grasp, and during manipulation per ADL (Supplementary material, S5). These profiles may be used to obtain the quantitative normative patterns of kinematics that will shed light on the demand required for common tasks to provide baselines to evaluate clinical populations.

The results described for kinematic hand synergies can be also applied in prosthetics, and possibly in industrial manipulation. Robotic hands that reproduce hand movements by modulating the main postural hand synergies have been recently presented [50], [51]. The results obtained herein (using standardised and representative ADL, and differentiating between reaching and manipulation phases) can greatly improve the usability of these prostheses. These biomechanical models can lead to prostheses that offer more functional adaptability and better interaction with the environment under real life conditions. Including reach-to-grasp and manipulation phases in biomechanical models and to improve prostheses make them more similar to real hands.

V. Conclusion

Hand kinematic analysis while performing complex and various ADL can benefit from the PCA method as the whole hand kinematics during such tasks was found to be actually low dimensional. Therefore, it can be efficiently described by only five kinematic variables: *digit arch, closeness, palmar-thumb coordination, thumb opposition,* and *thumb arch.*

Kinematic reduction provided a comprehensive study on hand movement in the reaching and manipulation phases. Reaching requires the modulation of synergies *closeness*, *digit arch* and *thumb opposition*, with different control patterns per grasp, while *thumb arch* and *palmar-thumb coordination arch* remain almost unchanged. On the contrary, all synergies need to be modulated during manipulation for all tasks. Kinematic reduction allowed to group ADL according to similar kinematic requirements, which may benefit the selection of tasks for both rehabilitation and hand function assessments.

The temporal evolution of the reduced kinematic variables is provided for a wide sample of healthy subjects during reaching per intended grasp and during manipulation per ADL. This scenario may help to improve the control of hand prostheses and to quantify the hand function assessment.

Finally, it is noteworthy that the used PCA method offers two key features compared to other studies: (i) characterises the hand kinematics without hiding the importance of the palmar arch and other DoF with small range of motion (e.g., fingers abduction), and (ii) obtains more sparse synergies by applying Varimax method, according to the most recent findings [23].

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