TITLE

Using kinematic reduction for studying grasping postures. An application to power and precision grasp of cylinders

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ABSTRACT

The kinematic analysis of human grasping is challenging because of the high number of degrees of freedom involved. The use of principal component and factorial analyses is proposed in the present study to reduce the hand kinematics dimensionality in the analysis of posture for ergonomic purposes, allowing for a comprehensive study without losing accuracy while also enabling velocity and acceleration analyses to be performed. A laboratory study was designed to analyse the effect of weight and diameter in the grasping posture for cylinders. This study measured the hand posture from six subjects when transporting cylinders of different weights and diameters with precision and power grasps. The hand posture was measured using a Vicon® motion-tracking system, and the principal component analysis was applied to reduce the kinematics dimensionality. Different ANOVAs were performed on the reduced kinematic variables to check the effect of weight and diameter of the cylinders, as well as that of the subject. The results show that the original twenty-three degrees of freedom of the hand were reduced to five, which were identified as *digit arching*, *closeness*, *palmar arching*, *finger adduction* and *thumb opposition*. Both cylinder diameter and weight significantly affected the precision grasping posture: diameter affects *closeness*, *palmar arching* and *opposition*, while weight affects *digit arching*, *palmar arching* and *closeness*. The power-grasping posture was mainly affected by the cylinder diameter, through *digit arching*, *closeness* and *opposition*. The grasping posture was largely affected by the subject factor and this effect couldn't be attributed only to hand size. In conclusion, this kinematic reduction allowed identifying the effect of the diameter and weight of the cylinders in a comprehensive way, being diameter more important than weight.

Keywords: hand posture, principal components analysis, cylindrical objects, grasp analysis

ABBREVIATIONS

3D:	3 dimensional
Ab/Ad:	Abduction/adduction
ANOVA:	Analysis of variance
CMC:	Carpometacarpal
DIP:	Distal interphalangeal
DoF:	Degrees of freedom
F/E:	Flexion/extension
HL:	Hand length
HB:	Hand breadth
IP:	Interphalangeal
MANOVA:	Multiple analysis of variance
MCP:	Metacarpophalangeal
MSV:	Mean square variance explained
PCA:	Principal component analysis
PCi:	Principal component i
PIP:	Proximal interphalangeal
RKVs:	Reduced kinematic variables
SD:	Standard deviation
Sig.:	Significance level
WMSD:	Work-related musculoskeletal disorders

1. INTRODUCTION

The human hand is a complex mechanical system that allows us to perform many activities of daily living, work, and recreation. Hand posture introduces constraints on the strength that can be exerted to complete a given task (Domalain et al., 2008; Rossi et al., 2012; Shivers et al., 2002; Watanabe et al., 2005), and affects the distribution of contact pressure and comfort rating (Aldien et al., 2005; Youakim, 2009). Hand posture also affects tendon loads and excursions, and stresses on adjacent tissues such as synovial membranes and nerves (An et al., 1983; Lee et al., 2008), which is associated with the risk of developing work-related musculoskeletal disorders (WMSD) (Laoopugsin and Laoopugsin, 2012; Wells et al., 1994). When attempting to prevent WMSD, different interventions are performed, such as controlling postures, lowering the required grasp force or changing the shape and size of the grasped surface, among others (Harih, 2014; Kroemer, 1989). Traditionally, when analyzing the upper limb posture to determine the risk of developing WMSD, the focus is set on shoulder and wrist postures, although recent work has also shown interest in recording all hand joints with more detail (Baker et al., 2007a, 2007b; Lee and Jung, 2015; Wang et al., 2015, 2014).

Hand posture analysis is hindered by the intrinsic kinematic complexity of the hand; using all joint angles might be cumbersome for describing hand shape, and focusing only on specific parameters might limit the results (Bae, 2011; Supuk et al., 2005). Observation-based assessments are more commonly used by occupational safety and health practitioners due to their affordability (David, 2005). In this sense, some recent studies have used video recording and posture classification to describe hand posture (Hwang et al., 2010; Vergara et al., 2014; Wang et al., 2015, 2014). However, these observation-based techniques are prone to problems caused by the hands being hidden by the handled objects and by other parts of the body, are very time-consuming, and are less reliable than the methods that register joint angles directly (David, 2005), named direct methods. Among these methods, instrumented gloves and videogrammetry have been used for ergonomic applications (Baker et al., 2007a, 2007b; Endo et al., 2007; Sánchez-Margallo et al., 2014; Yun, 1993). Direct methods also allow velocities and accelerations of movements to be obtained, which are critical for the analysis of WMSD (Juul-Kristensen et al., 2001; Marras and Schoenmarklin, 1993). Yet results obtained with so many degrees of freedom (DoF) are difficult to interpret, because of the need to observe the simultaneous variation of a large number of concatenated joint angles in different planes (Bae, 2011; Supuk et al., 2005).

A recent study proposed two metrics to describe hand shape registered by direct methods in a more comprehensive way than using the angles of all DoF (Bae, 2011): *openness* indicates the positions of the fingertips based on metacarpophalangeal (MCP) joint angles, while *flatness* indicates the extent to which each finger is flat or curved, based on the proximal interphalangeal (PIP) joint angles. These metrics were employed to test the effects of object size and shape on hand shaping during grasping. Limitations are apparent, as both metrics are related only to finger MCP and PIP flexion.

Although hand motion has many DoF, not all the joint movements are independent, because of mechanical and neural coupling. Mechanical coupling is due to connections between tendons and multidigit insertions of extrinsic finger muscles (el-Badawi et al., 1995; Tubiana and Valentin, 1964; von Schroeder et al., 1990), and neural coupling comes from the innervation of multiple spinal motor neuron pools from a single cortical motor neuron (McKiernan et al., 1998; Santello et al., 2013; Schieber et al., 2001). The coordinated movements between various joints resulting from these couplings are referred to as kinematic synergies (Bernshteĭn, 1967).

Based on principal component analysis (PCA), Santello and collaborators found support for the existence of static postural synergies, so that the hand shape can be predicted using a reduced set of variables, or postural synergies (Santello and Soechting, 1998; Santello et al., 2002, 1998). PCA is a statistical procedure that uses an orthogonal transformation to transform a set of correlated variables into a smaller set of linearly uncorrelated variables called principal components (PCs). In a recent study (Thakur et al., 2008), 17 subjects were asked to perform an unconstrained haptic exploration task over 50 different objects, identifying nine PCs, i.e., synergies, that were similar across subjects and across manipulations of different objects and accounted for more than 90% of the variance in the hand postures registered throughout all tasks. It was suggested that these synergies represented the basic building blocks underlying natural hand motions and may be used to represent hand posture and movements, thereby reducing the dimensionality of the results.

Furthermore, these synergies may also be used to measure hand postures in ergonomics studies in order to improve the design of handles and other parameters of the products that affect the way they are grasped and manipulated. Previous studies have shown that object size and shape cause different grasp execution (Cuijpers et al., 2004; Domalain et al., 2008; Meulenbroek et al., 2001; Santello and Soechting, 1998): the hand adapts its aperture to the size and shape of the object in an attempt to avoid collisions, especially with the fingers; this adaptation is not uniform, but increases dramatically during the last phase of grasp execution; thick objects (envelop diameter > 4 cm) tend to be grasped with all digits, while only the thumb and the index and middle fingers are used to grasp thin objects. Fewer studies have addressed the effect of an object's weight on hand posture. Weir et al. (1991) found a small but significant effect of the weight of the object on thumb and index finger motion during prehension of a metallic dowel. A significant influence of object size and weight on grip force during manipulation has been found (Jordan et al., 2005; Kinoshita et al., 1997; Vigouroux et al., 2011) and, consequently, hand kinematics might be modified by the central nervous system to apply grip force in a more efficient way. More knowledge is therefore required about the whole hand posture while grasping objects of different weights (Lee and Jung, 2015, 2014). Finally, hand posture is expected to be dependent on the subject. One personal factor that has been repeatedly studied is the relationship between hand size (mainly hand length) and object size (Seo and Armstrong, 2008), although the way the central nervous system adapts the musculoskeletal configuration to the grasping of objects may be different for different people. In a previous study (Mora et al., 2012), hand size was in fact postulated to account for the subject effect in an artificial neural network aimed at predicting hand posture, with poor results, thus indicating that the subject effect could not be reduced to hand size.

In this work we present a method to reduce the kinematic dimensionality of the hand posture, which can be used for ergonomics analyses, so that the complexity is reduced while keeping most of the information. In particular, we applied PCA to reduce the hand kinematics while grasping cylinders, and studied the effect of the cylinder diameter and weight on the grasping posture for precision and power grasps. We also verify whether hand size is able to account for subject posture variability for these grasps.

2. MATERIAL AND METHODS

2.1. Kinematic reduction of DoF using Principal Component Analysis

The method proposed for the kinematic reduction is to perform a PCA based on eigenvalue decomposition of a data correlation matrix (Daffertshofer et al., 2004; Hair et al., 2009) on all the hand joint angles registered. Each observation (grasping posture) consists of a row vector of 23 variables (the hand joint angles). The correlation matrix (23 x 23) is then built with the sums of the squares and cross products from the standardized data, by setting all variances equal to one. The sample size required to be able to apply PCA should be 100 observations or larger (Hair et al., 2009); as a general rule, there should be at least 5 (recommended 10) times as many observations as the number of variables (angles registered) to be analyzed. The criterion recommended to extract the PCs is the latent root criterion in which all eigenvalues > 1, so that each PC accounts for the variance of at least one of the original variables. This method is more reliable when the number of variables is between 20 and 50 (Hair et al., 2009). Prior to computation of the PCs, the joint angles should be rescaled to unit variance (Daffertshofer et al., 2004) to prevent the first modes from reflecting the joint angles with the largest amplitudes (flexion of MCP joints are expected to vary more than abduction of these joints). Communalities can be used as indicators of the reliability of the PC extraction, as they show how much of the variance in each of the original variables is explained by the extracted factors. The interpretation of the PCs in terms of the original variables is always useful to understand how the movement of the joints is coordinated. In order to achieve simpler and more meaningful solutions, Varimax rotation can be used to simplify the interpretation of the PCs (Hair et al., 2009), so that each PC represents mainly a small number of the original joint angles. To calculate the new variables that substitute the original ones, factorial analysis with PCA and the subsequent regression method for computing normalized factor scores (mean = 0, *SD* = 1) can be applied. These factors or reduced kinematic variables (*RKVs*) represent the same PCs and can be interpreted from their correlations with the original variables.

The method of reduction presented here can be applied to a set of observations corresponding to each frame of different trials, but in this paper it was applied to a set of observations consisting of one posture per trial, as we were interested in analyzing the hand grasping posture and not the postures during the grasp planning and object release stages.

2.2. Application to grasping of cylinders: Experiment to collect data

Six right-handed subjects participated in two experiments (approved by the University Ethics Committee) performed simultaneously. Subjects grasped paper-covered cylinders, so as to provide the same friction coefficient, of different diameters in Experiment I, and of different weights in Experiment II (Table 1). The range of diameters and weights for the cylinders was selected to cover those observed in a previous field study about ADL performed by the authors (Vergara et al., 2014), for the specific types of grasps considered in this study. All subjects gave their informed consent to participate in the experiments.

Table 1. Descriptive data of subjects participating in the experiments, and cylinders used.

Subject	Sex	Age (years)	HL (mm)	HB (mm)
1	Female	37	163.5	69.5
2	Female	22	170.0	73.0
3	Female	42	173.0	72.5
4	Male	45	186.0	88.0
5	Male	30	173.0	81.0
6	Male	39	193.0	89.0

	Experiment I				Experiment II			
Cylinder Id	1	2	3	4	5	2	6	7
Diameter (mm)	35	50	65	90	50	50	50	50
Height (mm)	200	200	200	200	200	200	200	200
Weight (g)	469	469	469	469	193	469	780	1117

Note. HL: hand length (from the proximal palmar crease to the tip of the third digit), HB: hand breath (at the metacarpal heads).

Each subject was seated at a table, with his/her right arm lying on the table in a relaxed posture and the hand placed about 15 cm away from the cylinder to be grasped. The subject was asked to grasp each cylinder and move it forward about 15 cm while keeping it in a vertical upright position, and then return the hand to the initial location. Each cylinder was grasped with a prismatic precision grasp involving all fingers and thumb tips, and a cylindrical power grasp (Figure 1). Each subject repeated both grasps on each cylinder, until completing three consecutive repetitions of each combination of grasp type and cylinder (after three previous and non-recorded training trials) in a single session. The order of the seven cylinders was set at random for each subject.

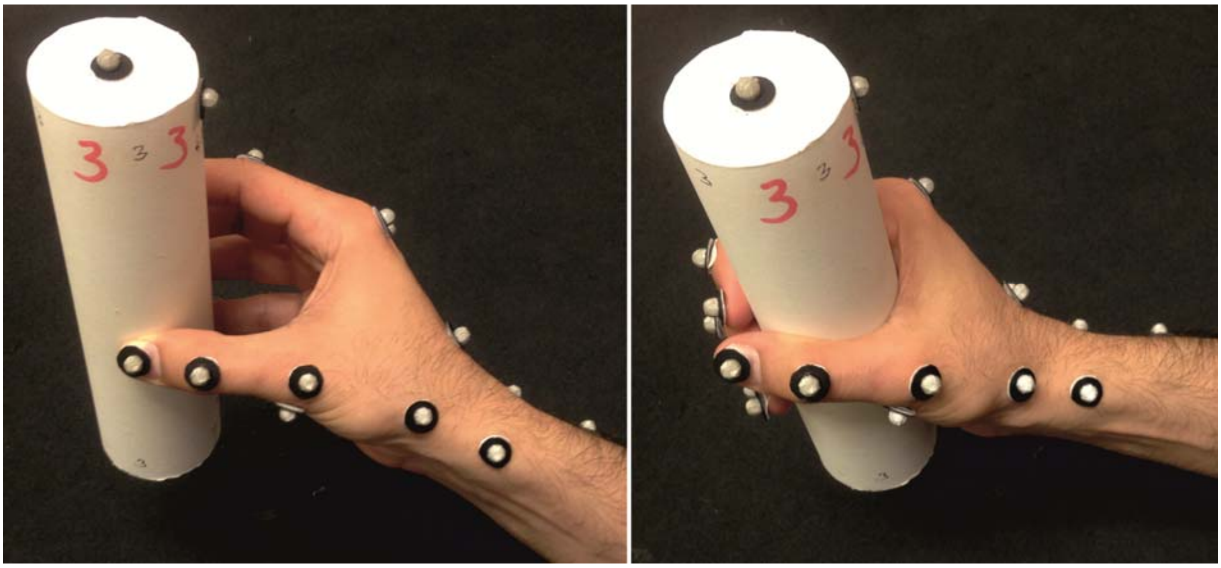

Figure 1. Types of grasps: left, all fingers and thumb prismatic precision grasp; right, cylindrical power grasp.

The hand posture and the cylinder position, and orientation were registered using a Vicon® motion-tracking system composed of eight Bonita® infrared cameras. The *3D* positions of 32 reflective markers (3 on the object and 29 on the hand) were recorded (Figure 2) with a 100 Hz sampling frequency, and the 23 joint angles defining the hand posture were obtained using the method described in a previous work (Sancho-Bru et al., 2014): flexion/extension (F/E) and abduction/adduction (Ab/Ad) at the carpometacarpal (CMC) joint of the thumb and all the MCP joints of the thumb and fingers, and F/E at the interphalangeal (IP) joint of the thumb, all PIP and distal interphalangeal (DIP) joints, and at the CMC joints of the ring and little fingers. Flexion rotations and ulnar deviations were considered positive at all joints.

The grasping postures used for the subsequent statistical analysis were those corresponding to the instant in which the object was at the maximal height, ensuring that the subject's hand was grasping it securely.

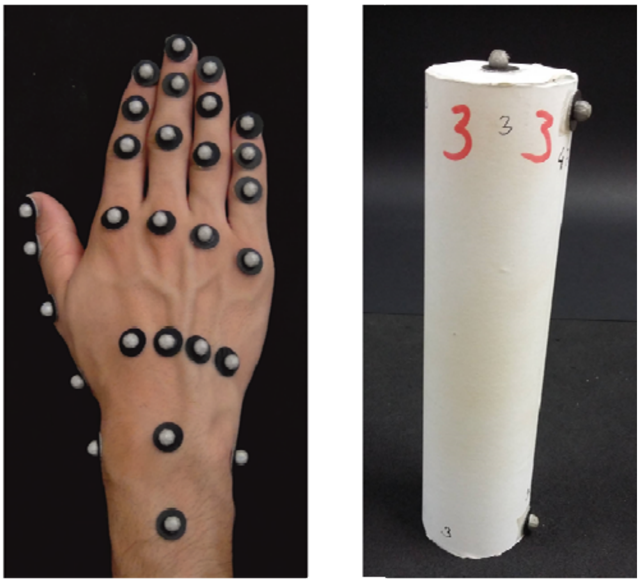

Figure 2. Detail of the location of the reflective markers used on the hand and on the cylinder.

2.3. Application to grasping of cylinders: Statistical analyses

The following statistical analyses were performed using the SPSS® Statistics software program:

(i) Kinematic reduction: the method described in section 2.1 was applied to the 23 joint angles registered in both experiments together and with the data of all subjects jointly, in order to extract the PCs, named PC_i. Thus, the number of postures registered included in the analysis was 252 (7 cylinders x 2 grasps x 6 subjects x 3 repetitions), which is enough to perform the analysis. Varimax rotation was used to simplify interpretation and the reduced kinematic variables (*RKVs*) were calculated.

(ii) Cylinder diameter and weight effect analysis: as an application for ergonomics, the global influence of diameter and weight was analyzed by means of two MANOVAs on the RKVs as dependent variables, and with *diameter* (*weight*, for the second analysis), *grasp type*, *subject,* and all their second-order interactions as independent variables (factors), over a total of 144 cases in each analysis (6 subjects x 2 grasps x 4 diameters or weights x 3 repetitions). The specific effect on each *RKV* was analyzed by means of ANOVAs on the *RKVs* as dependent variables, and with

the factors that were statistically significant in the MANOVAs. The mean values of the *RKVs* were plotted for each *grasp type* against the *diameter* and *weight* to identify potential trends.

(iii) *Subject/Hand size effect verification*: as the factor *subject* was significant in the MANOVAs and ANOVAs performed in (ii), as an application for ergonomics, additional analyses were performed to check whether *hand size*, represented by *HB* (hand breadth), *HL* (hand length) or *HB·HL*, could explain this effect. Mean values of the *RKVs* were analyzed to identify potential trends when changing hand size. Furthermore, for each experiment, the variance explained by hand size was compared to the variance explained by the subject in two sets of ANOVAs: one set conducted on each *RKV* as the dependent variable, and with the factors *subject*, *grasp type* and *diameter* (or *weight*), and another set conducted on the same *RKV* as the dependent variable, but with *HB·HL* as a covariable, and *grasp type,* and *diameter* (or *weight*) as factors. Box-and-whisker plots were also used to show differences in the *RKVs* among subjects. Finally, as it was observed that the variance explained by the *subject* was greater than that of *hand size*, a hierarchical clustering analysis was performed for each grasp type to identify similarities in grasping postures between subjects. The data were collapsed so as to have only a single value for each of the *RKVs* (mean value) for each subject, for each of the two grasp types considered. The hierarchical analyses consisted of agglomerative clustering with centroid linkage criterion, and Euclidean distance metric.

3. RESULTS

3.1. Kinematic reduction

The communalities observed in the PCA were high (mean 0.82, *SD* 0.13), which is an indicator of the reliability of *PC* extraction. Five PCs were extracted, which accounted for 82% of the total variance, the first two being responsible for 52% of this variance. Table 2 shows the correlations of these PCs with the original variables and Figure 3 represents the first four PCs graphically.

PC_1 represents mostly DIP and PIP flexion of fingers. PC_2 shows MCP flexion of fingers. PC_3 combines the palmar arching (ring and little CMC flexion) with thumb CMC adduction. PC_4 represents ulnar deviation of index, middle and ring MCP joints, accompanied by some palmar arching and little MCP adduction. Finally, PC_5 shows thumb MCP adduction with some palmar arching.

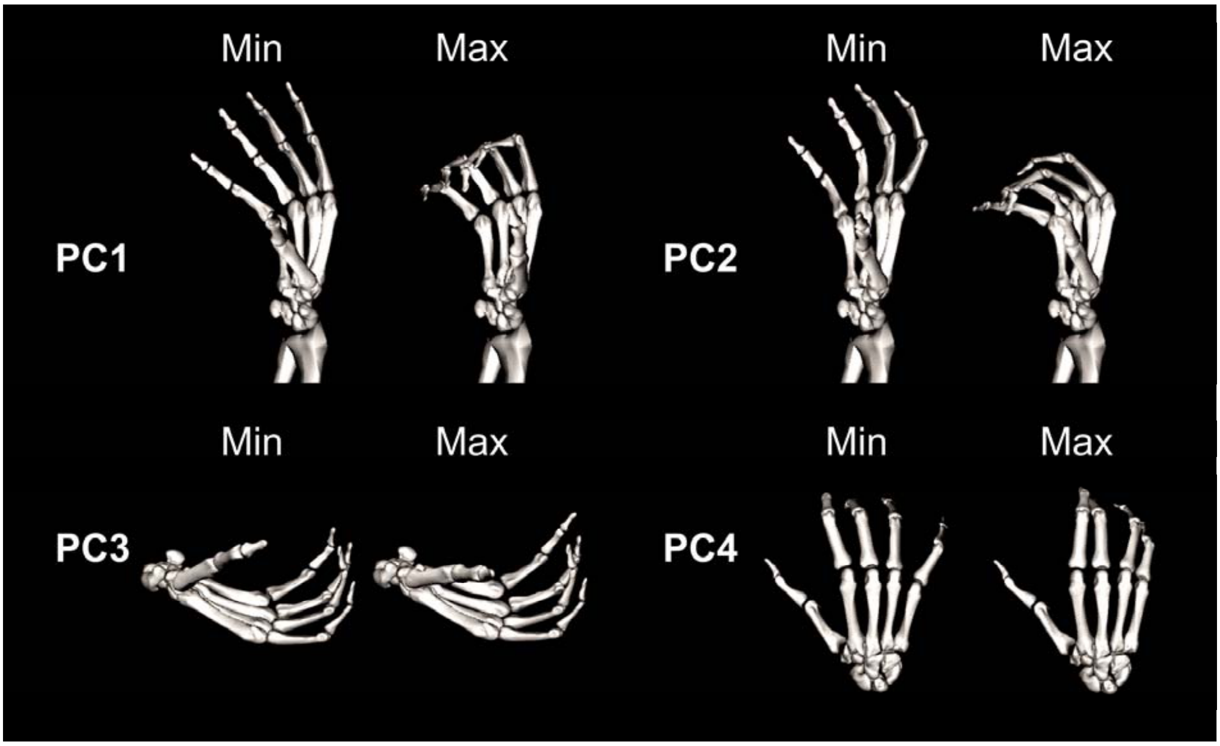

Figure 3. Mean extreme postures representing the first four PCs obtained after the kinematic reduction throughout experiments I and II altogether. The PCs are visualized using the hand kinematic model developed in Opensim by the ARMS lab of the Rehabilitation Institute of Chicago (Buffi et al., 2013; Holzbaur et al., 2005). This figure is complementary to Table 2, where the main joints involved in each PC appear in bold.

Table 2. Rotated component matrix for the 5 PCs extracted, showing the correlations between each of the original variables and the estimated PCs.

Original variables			Estimated PCs				
Digit	Joint	Movement	PC_1	PC_2	PC_3	PC_4	PC_5
Thumb	CMC	F/E	**-0.613**				
	CMC	Ab/Ad			**0.814**		
	MCP	F/E	**0.618**	0.385			-0.422
	MCP	Ab/Ad					**0.799**
	IP	F/E	0.511				
Index	MCP	F/E		**0.958**			
	MCP	Ab/Ad				**0.894**	
	PIP	F/E	**0.914**				
	DIP	F/E	**0.875**				
Middle	MCP	F/E		**0.968**			
	MCP	Ab/Ad		-0.564	-0.431	0.379	
	PIP	F/E	**0.960**				
	DIP	F/E	**0.774**	0.397			
Ring	CMC	F/E			**0.665**	0.327	0.564
	MCP	F/E		**0.943**			
	MCP	Ab/Ad				**0.845**	
	PIP	F/E	**0.940**				
	DIP	F/E	**0.724**	0.393			
Little	CMC	F/E			**0.815**		0.403
	MCP	F/E		**0.891**			
	MCP	Ab/Ad	-0.511			-0.508	
	PIP	F/E	**0.940**				
	DIP	F/E	**0.730**		-0.486		

Note. To simplify the interpretation of results, correlations smaller than 0.3 have been removed and those greater than 0.6 have been marked in bold.

3.2. Cylinder diameter and weight effect

All factors were found to significantly affect the *RKVs* ($p<0.001$) in both MANOVAs performed (Table 3). All univariate models were significant ($p<0.001$), and explained more than 88% of the variance in the *RKVs*. In Experiment I (diameter effect), all the factors significantly affected all the *RKVs* ($p<.05$), the only exception being *grasp type x diameter* on RKV_5. Analogously, in Experiment II (weight effect), *subject*, *grasp type*, and the interaction *grasp type x subject* were found to significantly affect all *RKVs* ($p<.05$), while weight affected all *RKVs* except RKV_4, the interaction *grasp type x weight* affected all *RKVs* except RKV_5, and the interaction *subject x* *weight* only significantly affected RKV_2, RKV_4 and RKV_5. Note that the variance explained by the factor *subject* in both experiments is high in all *RKVs*, except in RKV_1, whose variance was basically explained by the factor *grasp type*. In Experiment I, however, the factor *diameter* explained more variance than *subject*. And the variance explained by *diameter* in Experiment I was higher than that explained by *weight* in Experiment II.

Table 3. Results of the ANOVAs on the *RKVs* in experiments I and II.

	Experiment I			Experiment II		
Dependent variable	Source	MSV	Sig.	Source	MSV	Sig.
RKV_1	*grasp type*	75.865	0.000	*grasp type*	128.257	0.000
RKV_2		6.318	0.000		1.592	0.000
RKV_3		3.610	0.000		7.659	0.000
RKV_4		0.487	0.004		1.050	0.000
RKV_5		5.743	0.000		9.976	0.000
RKV_1	*subject*	2.216	0.000	*subject*	2.670	0.000
RKV_2		11.703	0.000		12.219	0.000
RKV_3		17.320	0.000		22.377	0.000
RKV_4		26.707	0.000		21.207	0.000
RKV_5		15.394	0.000		14.958	0.000
RKV_1	*diameter*	2.790	0.000	*weight*	0.242	0.000
RKV_2		21.837	0.000		0.749	0.000
RKV_3		4.818	0.000		1.137	0.000
RKV_4		1.415	0.000		0.040	0.325
RKV_5		4.675	0.000		0.279	0.008
RKV_1	*grasp type x diameter*	5.030	0.000	*grasp type x weight*	0.268	0.000
RKV_2		1.985	0.000		0.598	0.000
RKV_3		2.669	0.000		0.386	0.000
RKV_4		0.192	0.019		0.114	0.023
RKV_5		0.422	0.061		0.062	0.430
RKV_1	*subject x diameter*	0.127	0.000	*subject x weight*	0.024	0.053
RKV_2		0.438	0.000		0.100	0.015
RKV_3		0.356	0.000		0.051	0.361
RKV_4		0.267	0.000		0.143	0.000
RKV_5		0.879	0.000		0.183	0.001
RKV_1	*grasp type x subject*	1.166	0.000	*grasp type x subject*	2.005	0.000
RKV_2		1.772	0.000		5.676	0.000
RKV_3		1.267	0.000		2.751	0.000
RKV_4		0.983	0.000		2.277	0.000
RKV_5		4.824	0.000		6.031	0.000

Note. MSV: Mean square variance explained, Sig.: Significance level.

Figure 4 shows the mean values of the *RKVs* plotted against *diameter* and *weight*, distinguishing by *grasp type*. The diameter variation generated greater changes in the *RKVs* than the weight variation. Moreover, values and trends of the *RKVs* differed among grasp types when varying the diameter or weight. All *RKVs* showed a trend when varying the diameter, except RKV_3 in power grasp. This may be due to the different zones of contact of the palm with the cylinder depending on the diameter of the cylinder. We observed that cylinders 1 and 2 were grasped with the whole palm in firm contact with the cylinder, while cylinder 3 was grasped without making contact with the hypothenar eminence, and cylinder 4 without contact with the hypothenar or the thenar eminences. All other *RKVs* showed a general decrease when increasing the diameter, except RKV_5 in both grasp types and RKV_1 in the precision grasp, which exhibited an increase. Weight variation did not produce any big changes in the *RKVs* in the case of the power grasp. An additional ANOVA on *RKVs* restricted to power grasps (not shown for the sake of brevity) revealed no significant differences in RKV_2, RKV_3 and RKV_4 for the factor *weight*.

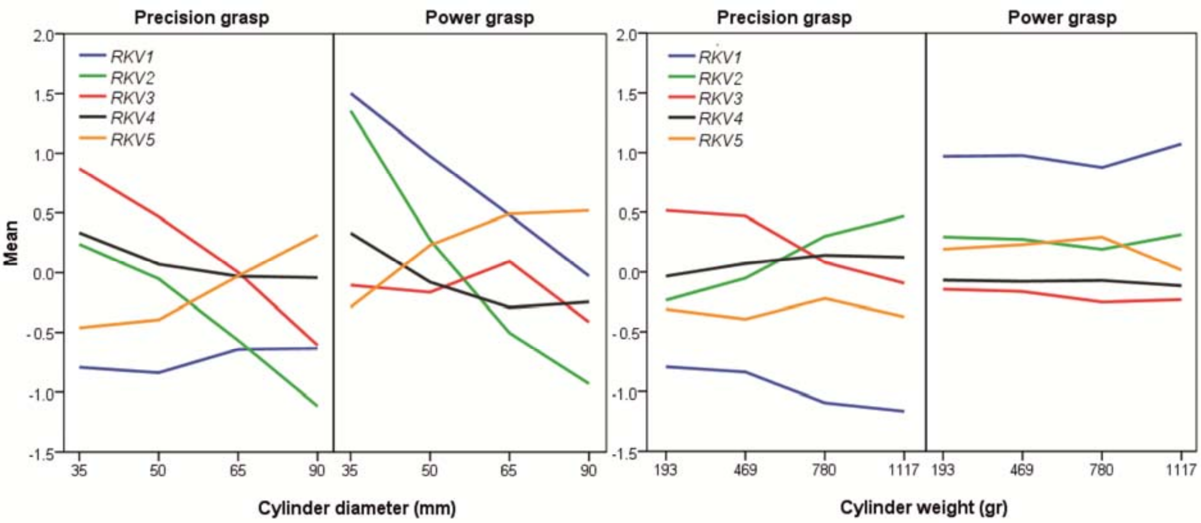

Figure 4. Evolution of the mean values of the *RKVs* when varying the cylinder diameter (left) and cylinder weight (right) obtained from Experiment I and II, respectively, for both types of grasp.

3.3. Subject/Hand size effect

Results from the ANOVAs in the previous section revealed a significant subject effect on all *RKVs* in both experiments, *subject* explaining a high variance in all *RKVs*, except in RKV_1. Different analyses were performed looking for a relationship between the *RKVs* and the parameters *HB*, *HL* and *HB·HL*, representative of hand size, with unproductive results. As an example, the plots of the mean values of the *RKVs* against *HB·HL* were reflected distinguishing by *diameter* and *weight*, for the precision grasp (Figure 5). No clear trend was observed for the *RKVs* with hand size, except perhaps for RKV_2, which seems to present higher values for larger hand sizes. These results, nonetheless, must be taken with care, as only six hand sizes were used.

The variances explained by the two sets of ANOVAs, with the factor *subject* or with *HB·HL* as a covariable, are shown in Table 4, together with the R squared coefficient of the model (which measures the percentage of variance explained by the model). The variances explained by the univariate models that used *HB·HL* as a covariable were lower in both experiments than the variances explained by those using the *subject* factor. Furthermore, in the models with *HB·HL*, the R coefficients are low, especially for RKV_3, RKV_4 and RKV_5 in both experiments, and also for RKV_2 in Experiment II.

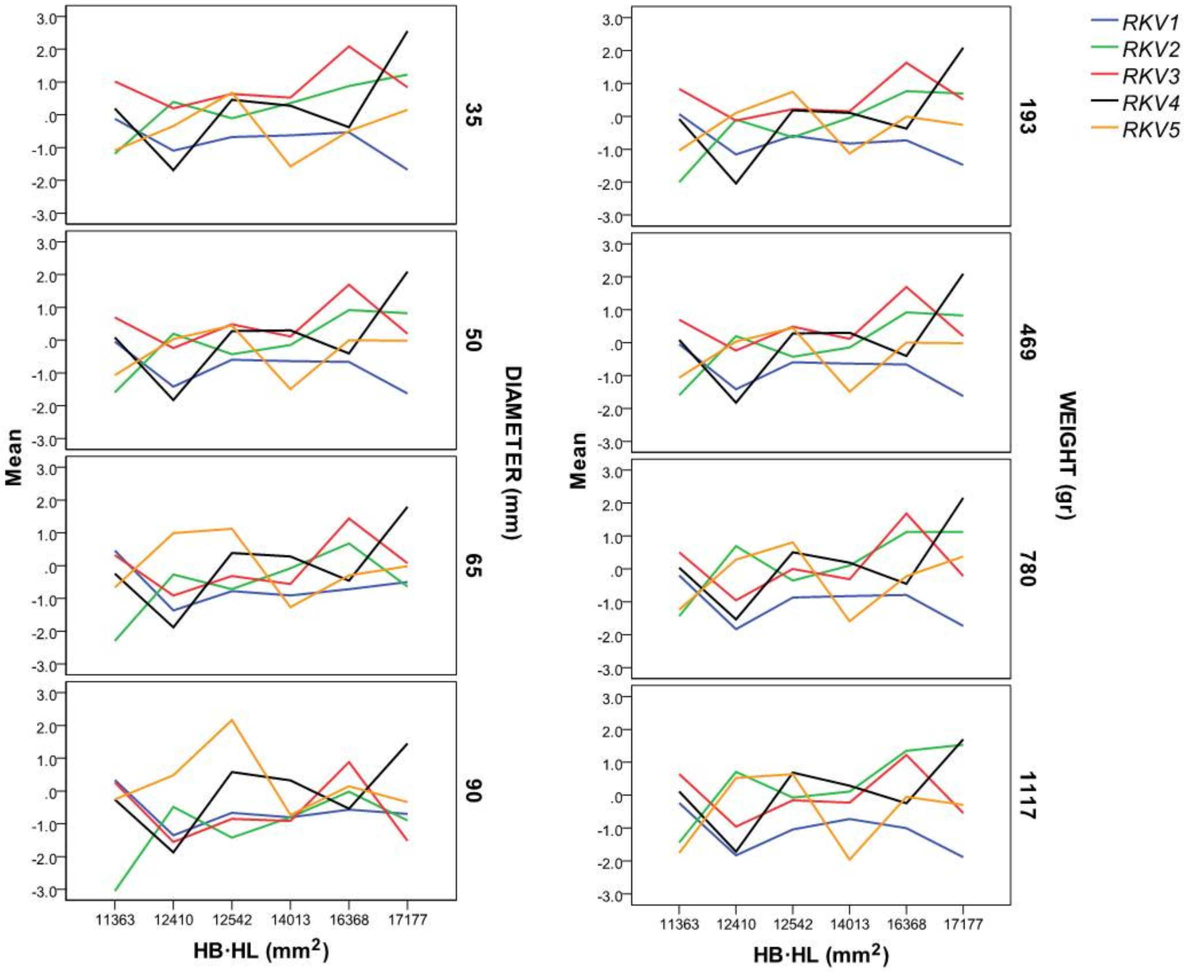

Figure 5. Mean values of the *RKVs* against *HB·HL*, for the precision grasp, distinguishing by cylinder diameter (left) and weight (right).

Table 4. Results of the two sets of univariate analyses performed for both experiments on all *RKVs* to compare the variances explained by the subject and the hand size, represented by *HB·HL*.

	Experiment I				Experiment II			
	Subject [a]		*HB·HL* [b]		*Subject* [c]		*HB·HL* [d]	
Dependent variable	EV	R^2	EV	R^2	EV	R^2	EV	R^2
RKV_1	111.1	0.906	100.4	0.820	147.7	0.925	135.4	0.849
RKV_2	138.2	0.880	103.0	0.656	65.5	0.651	24.2	0.241
RKV_3	114.1	0.832	28.2	0.206	126.1	0.864	16.4	0.112
RKV_4	140.7	0.903	36.9	0.237	109.1	0.863	28.4	0.225
RKV_5	94.0	0.631	25.0	0.168	84.2	0.677	15.7	0.127

Note. EV: Explained variance, R^2: R squared coefficient of the model

a. Factors: *subject*, *grasp type* and *diameter*.
b. Covariable: *HB·HL*. Factors: *grasp type* and *diameter*.
c. Factors: *subject*, *grasp type* and *weight*.
d. Covariable: *HB·HL*. Factors: *grasp type* and *weight*.

Figure 6 shows box-and-whisker plots of the *RKVs* for each subject and all the data (both experiments together), where each subject is observed to use very different values and ranges of the *RKVs*. Figure 7 shows a dendogram with the results from the hierarchical clustering analyses. Different groupings were obtained for each grasp type. While subjects 1 and 5, and 3 and 6 were found to perform the precision grasp in a similar way, subjects 5 and 6, and 1 and 4 performed the power grasp similarly.

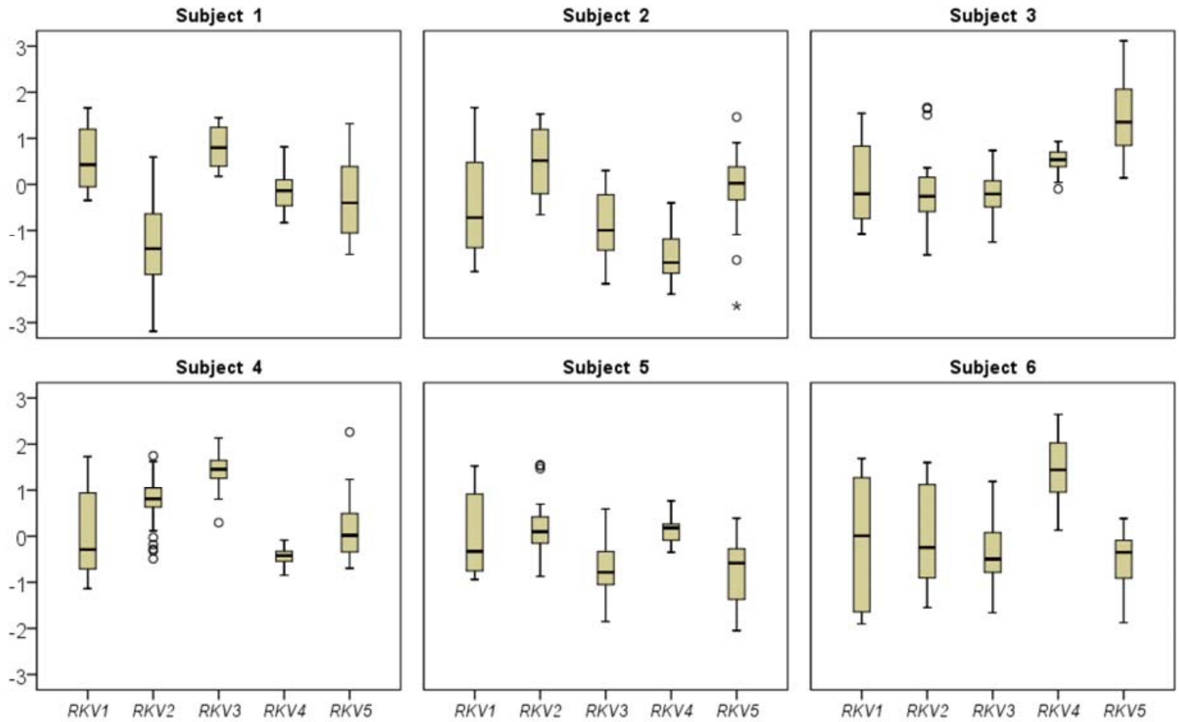

Figure 6. Box-and-whisker plots of the *RKVs* for each subject in Experiments I and II together.

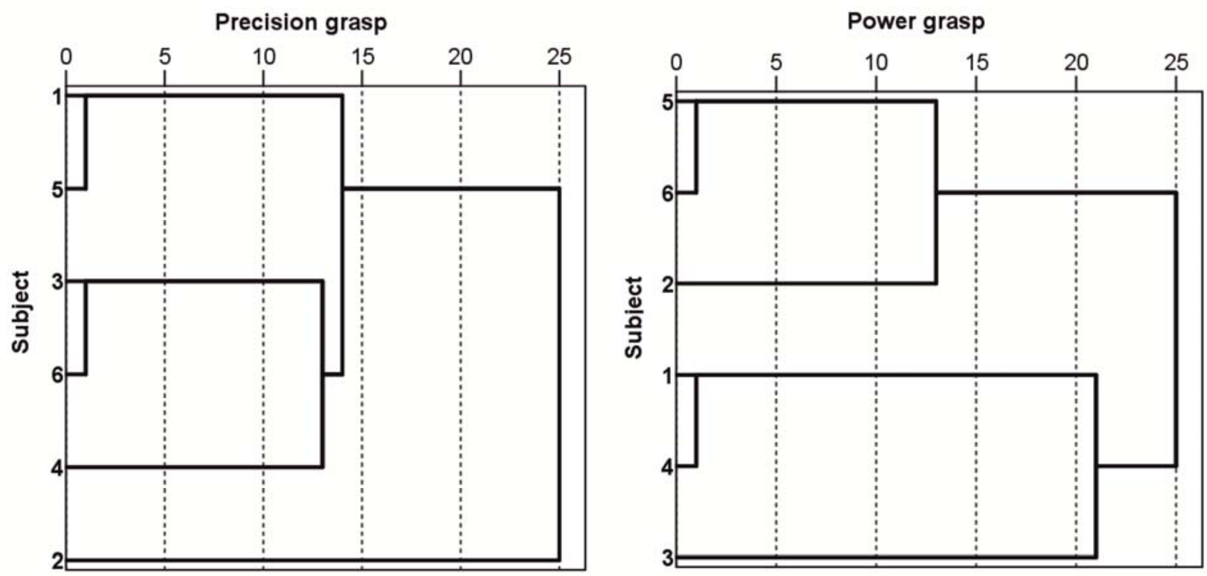

Figure 7. Dendrograms resulting from the hierarchical clustering analyses: left, for precision grasp; right, for power grasp. Vertical lines represent clusters, and distances from 0 of these lines represents similarity (the closer to 0, the more similar they are).

4. DISCUSSION

Hand posture analysis in ergonomics can benefit from the use of PCA and factorial analysis by allowing the dimensionality of the problem to be reduced. In particular, we have confirmed that the whole hand grasping kinematics is actually low dimensional and can be efficiently described by a small number of reduced variables (5 RKVs) for precision and power grasps of cylinders with all fingers. This new set of variables provide the same information but in a more easily interpretable way: RKV1 represents mostly DIP and PIP flexion of fingers, i.e., the digit arching (opposed to flatness); RKV2 represents MCP flexion of fingers, i.e., the closeness (opposed to openness); RKV3 represents ring and little CMC flexion with thumb CMC adduction, i.e., the palmar arching (like holding water with the hands); RKV4 represents finger adduction; and finally, RKV5 represents thumb MCP adduction with some palmar arching, i.e., opposition.

Note that the *RKVs* found in this study might not suffice to represent the postures adopted for grasping other products with a more complex shape, but the advantages of the method are also applicable to grasping a greater variety of objects. The first two RKVs, each associated to the PCs obtained in this same study, match those PCs obtained in previous research on similar grasps (Mason et al., 2001; Santello et al., 1998; Todorov and Ghahramani, 2004). However, the number of PCs obtained in this work is higher than that reported in those studies, but much smaller than the number of PCs obtained by Thakur and collaborators (Thakur et al., 2008). One of the main reasons for this is that the number of DoF measured both here and in Thakur's work is higher. In particular, previous studies in the literature have not registered the movements at the ring and little CMC joints, and were therefore unable to observe the palmar arching that has been found here, as well as in Thakur's work, as an important factor to represent the grasping posture. Another reason is that previous studies (Mason et al., 2001; Santello et al., 1998; Todorov and Ghahramani, 2004) considered only the movements during the planning of the grasping of imaginary objects, so that adapting the posture to the real object shape was neglected, as these works focused on investigating hand control and not on studying the posture during grasping. The number of PCs obtained by Thakur and collaborators was higher than in this work because they studied the whole process of manipulating very diverse objects by a large number of subjects in order to find the basic synergies underlying any natural hand motion, while in this work the objects are limited to cylinders, and the action to holding.

The use of the *RKVs* to study hand posture is a good compromise between simplicity of posture representation and accuracy. Previous metrics, such as openness and flatness used by Bae (Bae, 2011), are very limited as they do not provide information on palmar arching, thumb motion or finger abduction, which have been shown to be important aspects for characterizing hand posture.

Both the diameter and weight of the cylinder significantly affect the hand posture for precision and power grasping. However, the differences in variance explained by these factors reveal that diameter has a higher effect than weight, which matches previous results (Weir et al., 1991). Diameter variation significantly affects all *RKVs*, while weight variation affects all *RKVs* except *opposition*. Furthermore, both interactions *grasp type x diameter* and *grasp type x weight* significantly affect the *RKVs*, which means that the effect of the cylinder attributes was different depending on the *grasp type*. Furthermore, a different effect of *diameter* was identified depending on the *grasp type* considered for all *RKVs* except for *opposition*. To grasp wider cylinders using the precision grasp, subjects basically decrease *closeness* and *palmar arching* and increase *opposition*. Conversely, when using the power grasp with wider diameters, subjects mostly decrease *digit arching* and *closeness* and increase *opposition*. These results are coherent with those from previous works (Cuijpers et al., 2004; Domalain et al., 2008; Meulenbroek et al., 2001; Santello and Soechting, 1998), as they show that the hand adapts its aperture to the object size, but provide far more detailed comprehensive information. Different *weight* effects were also identified depending on the *grasp* type performed for all *RKVs* except for *finger adduction*. In fact, very small changes in the *RKVs* are observed when varying the weight in the power grasp (significant differences were found only on *digit arching* and *opposition* with *weight*), while the differences in the precision grasp are higher. The increase in weight in the precision grasp was counteracted with lower values for *digit arching* and *palmar arching* and an increase for *closeness*. This agrees with the fact that additional flexion strength requires intrinsic muscle collaboration, which generates flexion on MCP joints and extension on PIP and DIP joints (Brand and Hollister, 1999). In the power grasp, postures do not change so much, as the grasp forces required are far from their limits and the hand posture is conditioned by the cylinder geometry being grasped.

The values of *digit arching* are always higher for the power than for the precision grasp and the variance explained by *grasp type* in both cases for *digit arching* is very high compared with the other factors, so that this variable may help to distinguish between the two grasp types when grasping cylinders. Future work should consider a wider range of grasps and object shapes to study whether RKVs can be used as automatic predictors of the type of grasp being used at each instant. This would reduce time in analyzing videos of observational techniques with the advantage that velocities and accelerations could also be considered.

A significant effect of the *subject* factor has been identified on all *RKVs* when varying cylinder diameter or weight. Moreover, the *subject* was the factor that explained most of the variance in all *RKVs* (except for *digit arching*, which depends mainly on the grasp type, as stated above) in both experiments. It is obvious that hand size affects hand posture (Edgren et al., 2004), but we wanted to check whether the variance introduced by the subject in our experiments was mostly due to differences in hand anthropometry or to other factors, such as personal preferences or anatomical variations in the intertendinous connections, i.e., we wanted to evaluate the result of substituting the *subject* effect by the hand size in posture prediction. This hypothesis was discarded, as no relationship was observed between the mean values of the *RKVs* and hand size (represented by *HB·HL*, *HB* or *HL*), for the different cylinder diameters and weights, with any of the grasp types considered. The low variances explained by the univariate models that used *HB·HL* as a covariable, unlike the high variances explained by the univariate models that used the *subject* factor, confirm that the subject effect is complex, and only a small part of it might be explained by looking at hand anthropometry; basically, larger hand sizes seem to require higher *closeness*, in an effort to adapt the hand to the cylinder being grasped. Although these results have to be taken with caution because of the small number of subjects considered, we observed large differences in the overall ranges (mean and confidence interval) of the *RKVs* used by the different subjects participating in the experiments, which possibly implied the use of different strategies to accomplish the grasp. The hierarchical clustering analyses revealed some similarities in the grasping postures between different pairs of subjects for each grasp type, i.e., these pairs of subjects used the same strategy to perform a specific grasp type. Notice that most of the similarities found between pairs of subjects occurred for subjects with very different hand sizes, like subjects 1 and 5, 3 and 6, and 1 and 4. Pairs of subjects with similar grasping postures were different for each grasp type, which is consistent with the significant effect observed for the interaction *grasp type x subject*.

In short, by using kinematic reduction we have been able to show how the cylinder diameter and weight affect the hand posture in a comprehensive way. We have shown that both cylinder diameter and weight significantly affect precision grasping posture (diameter affects *closeness*, *palmar arching* and *opposition*, while weight affects *digit arching*, *palmar arching* and *closeness*), whereas the power-grasping posture is mainly affected by the cylinder diameter (which affects *digit arching*, *closeness* and *opposition*). In addition, we have seen that the factor *digit arching* could be used to distinguish automatically between the two grasp types studied. Finally, we have also shown that the *subject* factor is the one that most affects the hand posture, and that it makes a large contribution arising from factors other than hand size. Further studies involving a large varied number of subjects might help to identify the most common strategies for performing each grasp type.

The specific findings of the effect of the weight and size of the cylinders have to be taken with caution, because of the small number of subjects used in the study. Furthermore, we have to limit the validity of our particular results to holding cylinders within the range of weights and sizes considered in the experiments, but the method presented here to study the kinematics of hand posture can be useful to study the grasping posture for other objects and tasks, since the whole hand grasping kinematics has been shown in previous works to be actually low dimensional (Thakur et al., 2008). The study of the posture is essential in many ergonomic analyses and evaluations, and the analysis of the effect of different design parameters of the product being handled on the grasping posture is cumbersome when considering all hand DoF (Bae, 2011; Supuk et al., 2005). The application of the proposed method for reducing the hand kinematics has allowed an easier and more meaningful interpretation of the effect of diameter and weight on the grasping postures during precision and power grasps of cylinders.

6. CONCLUSIONS

Hand posture analysis in ergonomics can benefit from the use of PCA and factorial analysis, as the whole hand grasping kinematics is actually low dimensional. The use of the RKVs to study hand posture is a good compromise between simplicity of posture representation and accuracy.

Kinematic reduction has allowed a comprehensive study of the effect of cylinder diameter and weight on the hand posture. Both cylinder diameter and weight significantly affect the precision grasping posture: diameter affects *closeness*, *palmar arching* and *opposition*, while weight affects *digit arching*, *palmar arching* and *closeness*. The power-grasping posture is affected by the cylinder diameter, through *digit arching*, *closeness* and *opposition*. Finally, the factor *subject* has a large effect on the hand posture, with an important contribution arising from factors other than hand size.

A potential use of RKVs as automatic predictors of the type of grasp used at each instant has also been postulated, which would accelerate data processing of observational techniques, with the added value of allowing velocity and acceleration analysis.

7. ACKNOWLEDGMENTS

We are grateful to the Universitat Jaume I for financial support through project P1·1B2013-33, and the Spanish Ministry of Research and Innovation and the EU (FEDER funds) through projects DPI2010-18177 and DPI2014-52095-P.

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