Master's Thesis

Analysis of a Large Series of Hand Kinematics Measurements

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DLR

FAKULTÄT FÜR INFORMATIK

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Analysis of a Large Series of Hand Kinematics Measurements

Auswertung einer großen Reihe von Messungen menschlicher Handkinematik

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Date: November 15, 2013

Ich versichere, dass ich dieses Master-Thesis selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel verwendet habe.

I confirm that this master's thesis is my own work and I have documented all sources and material used.

München, 15.11.2013 Bojan Kolosnjaji

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Abstract

This thesis describes a unified model of human hand kinematics. Visual 3D measurements of human hand segment positions throughout different movements are used to determine Denavit-Hartenberg parameters and joint angles for both left and right hands of 110 subjects. These parameters are then transformed using PCA transformation to reveal the intrinsic dimensionality behind these parameters. PCA transforms of DH parameters and joint angles, both separately and together, show a significant correlation between parameters that can be exploited for dimensionality reduction.

Index Terms—**Hand Kinematics, Dimensionality Reduction, Generative Hand Model**

I. Introduction

In biomechanics the human hand can be modeled as a connected set of joints and links. Information from this kind of human hand models could be used in modeling and construction of anthropomorphic robotic hands that would mimic the human hand motion in a wide range of tasks such as grasping different objects. A long term goal of this could be construction of prosthetic hands or robots that carry out more sophisticated tasks that have been previously restricted to humans. General reference on the recent advances in this area is given in the paper of van der Smagt et al. [12]. Performing some tasks that are usually dedicated to humans requires the robotic hand to adapt to grasping tools of various form and size. Therefore it is important to know the key parameters of human hand kinematics that enable every human hand to execute these tasks, and abstract from the particular properties that constitute the differences between hands.

To create optimized models of human hand kinematics, the first step is the data acquisition. Data acquisition using bone and skin markers attached to the hand is described in the work of Lundberg [8]. There are multiple methods for performing hand kinematics measurements, from the usage of cadavers to invasive, semi-invasive, and non-invasive measurements using live subjects. Most used methods involve attaching markers to human hand and recording of marker positions through time while the subjects perform an assigned movement. Recording of marker positions is commonly done using optical 3D measurement systems (e.g. Cerveri et al. [2]). Optical 3D measurements can reach a very high frame rate, which increases the reliability of the results of further processing. An alternative is to use 3D MRI medical imaging (e.g. Stillfried et al. [11]), but here the frame rate usually cannot be as high.

After data acquisition optionally noise reduction techniques are used to clean up the measurements. The resulting data is used for the optimization of model parameters, with a goal to minimize the difference between measured positions of markers and modeled positions generated using the model parameters. Since the human hand has a high number of degrees of freedom (DoF), determining model parameters can be a complex optimization problem. There are multiple papers which deal with the issue of determining hand kinematics models. In the work of Zhang, Lee and Braido [13] centers of rotation for finger joints are optimized by minimizing the variation of link lengths over the different frames. The accent there was on investigating the skin motion to model its effects on measurements. Cerveri et al. [2] give a more extensive study of hand kinematics modeling and it is the first paper about whole-hand kinematics known to the author. Here both centers and axes of rotation are determined using an evolutionary optimization algorithm and data from an optical motion tracking system. In the work of Chang and Pollard [3], [4] more robust methods were developed for determining centers and axes of rotation. Gabiccini et al. [5] reconstruct hand posture from MRI images and investigate postural synergies.

Multiple existing papers suggest the possibility of creating generative, predictive hand models based on measurements carried on with different subjects, but there are not many such studies yet. One similar research was done by Buchholz et al [1]. In this paper the authors, using measurements from cadavers, estimate the relationship between joint parameters and other parameters of the human hand. Their model predicts joint center position based on length of the bone, lengths of kinematic segments and location of metacarpophalangeal (MCP) and carpometacarpal (CMC) joints based on the external hand length. Santello et al. [10] use PCA transformation to reveal principal components of joint angles and synergies between them. Their generative model, however, only considers dynamic parameters that change over time, but not static axis parameters.

The intention of this thesis is to initially use an existing large series of hand posture measurements from multiple subjects to derive optimized static models of hand kinematics for all subjects. The parameters of these models are statistically analyzed in order to create a generative, predictive hand model with a minimal number of parameters. This unified model describes the common properties of human hand kinematics and identifies the characteristics that are special for each individual hand. It should be possible to use this model to accurately predict hand kinematics of various subjects.

II. Method

A. Measurements and preprocessing

To capture the hand motion, optical measurements are carried out using a Vicon 3D optical motion capture system. There are 110 subjects participating in the experiment. For each subject, measurements are carried out while the subject is performing a variety of movements. The measurement frequency is 100 Hz. Markers are attached to various hand segments to capture the motion. Position of the markers is shown in Figure 1. Measurements are also made where the hand is in a flat posture, without movement. These are used as reference postures, with joint angles set to zero. All the measurements are preprocessed using the Vicon Nexus software, for proper labeling of the markers. Labeling is partially done using the mentioned software, but in part manually as well, due to problems with tracking markers through time. Quality of data is also enhanced using a median filter, to reduce the possibility of false labeling, which happens frequently in cases of fast grasp movements.

Tetrahedron marker stars are used to determine both position and orientation of a finger segment. The rotation matrix of a tetrahedron marker is determined using the method of Horn [7]. The point of origin of the marker star branches is used as the marker position. This point of origin is not measured, but it needs to be computed based on reference tetrahedron templates. A picture of tetrahedron markers is shown in Appendix A. Knowing the dimensions of a tetrahedron marker star and relative position of its markers, it is possible to determine the coordinates of the markers relative to the origin of the tetrahedron marker star. Using these coordinates and Horn's method in each time frame the coordinates of the origin of the tetrahedron are determined. As the Vicon measurement system does not provide information for differentiating different markers in a marker star, in each time sample a combination is determined that minimizes the least squares error. This way the full transformation matrix is used in the further modeling process. In case that the proper marker dimensions are not available, a custom marker star template is created. This is done using the measurements from the Vicon system for a specific marker star. For each pair of markers for a certain marker star a median of inter-marker distances is computed. Using this information a new template is created where the distances are equal to the computed medians. Since all that is needed is relative movement (rotational and translational) of a marker star between time samples, this kind of marker star template is satisfactory (see Appendix B).

B. Single-hand model

1) Model parameters: The kinematic model of a single hand posture consists of static (time-invariant) and dynamic axis parameters. Static parameters describe the properties of the hand and are used in a form described by a Denavit-Hartenberg (DH) notation, modified by Hayati et al [6]. Here there are two sets of parameters for each axis. If the axes are not nearly parallel, original DH parameters are used. In the nearly parallel case the original parameters cannot be uniquely determined. For that reason there is a different set of parameters, accommodated to this case. Dynamic parameters are the rotation angles that describe the rotation of the hand segments around the previously described axes. The rotation is measured relative to the reference measurements with flat posture. For every posture these parameters are different.

2) Initial DH parameter values: There are 5 axes chains identified for each hand, which correspond to each finger. Chains are set up in a way that one of the chains (thumb chain) begins from the base segment and the other chains begin from an axis in the thumb chain set up initially between the dorsal and forearm segment (at the wrist).

3) Choice of time samples: For each subject there is a large number of recorded samples ($\approx 10^4$). Since processing of all the time samples is not computationally feasible, the following procedure is used to select the time samples that will be used in the optimisation procedure. A 3D grid is created in space and marker positions, relative to the forearm marker, for all the time samples are placed in this grid, where each grid segment has a unique identifier. For each time sample, there is a vector that contains identifiers of grid segments where markers in this time sample are contained. For each distinct vector value, one of the time samples corresponding to this vector value is selected, based on the quality of measurements. The quality of measurements is inversely proportional to the number of unlabeled markers in the corresponding time sample. The number of time samples depends on the resolution of the grid. The resolution is chosen in a way that results with the number of time samples closest to 100.

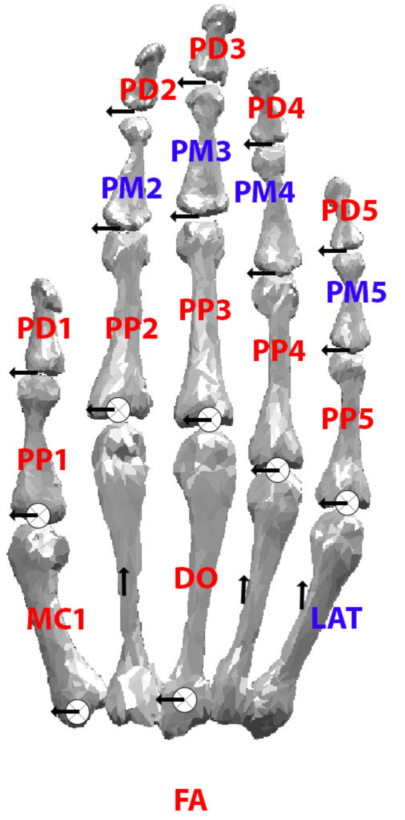

Figure 1: Display of the hand segments and approximate axes positions. Red color indicates full tetrahedron markers and blue color is for the single, position markers.

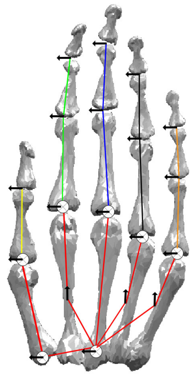

Figure 2: Parts of the hand optimized separately during the preliminary stage

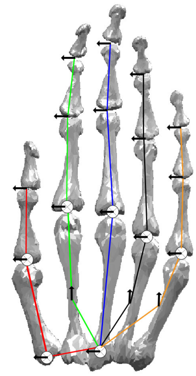

Figure 3: Axes chains optimized during the main optimization cycle

4) Optimization scheme: For each single hand, both static and dynamic parameters are optimized. The vector of parameters to be optimized consists of DH parameters of the hand and sets of rotation angles, different for every posture. In addition, the optimization scheme contains the optimization of reference postures, to neutralize the error of reference posture measurements as well as the optimization of the base frame transformation. An additional set of parameters is needed to describe the skin movement. Analysis of the model parameter results initially indicated a bigger error for the dorsal marker because of a significant skin movement in this part of the hand. This movement is then modeled as linearly dependent of the rotation angle of the third finger. The coefficient of this linear model is added as an additional parameter in the optimization. Based on the parameter values a cost function is calculated in each iteration and a gradient-based optimization (with first order gradient) is used to find a minimum of this function.

The cost function is computed as follows:

$$C = \frac{1}{T}\frac{1}{N}\sum_{t=1}^{T}\sum_{n=1}^{N} w_{\mathrm{t}} d_{\mathrm{t}}(T_{\mathrm{mod}}^{\mathrm{n,t}}, T_{\mathrm{meas}}^{\mathrm{n,t}}) + w_{\mathrm{r}} d_{\mathrm{r}}(T_{\mathrm{mod}}^{\mathrm{n,t}}, T_{\mathrm{meas}}^{\mathrm{n,t}}),$$

where T_{mod} are the modeled, and the T_{meas} are the measured transformation matrices. For each segment marker, the translational (d_{t}) and rotational (d_{r}) distances are computed. A weighted sum of these distances for all markers (n) and all time samples (t) represents the cumulative cost function for a set of model parameters. Weight values used in the optimization are: $w_{\mathrm{r}} = \frac{180}{\pi} rad^{-1}$ and $w_{\mathrm{t}} = 1mm^{-1}$. The weight values are chosen so that the cost function values correspond to a rotational distance in degrees and translational distance in millimeters. This intuitively makes the changes in the two parts of cost function comparable. Translational distances are computed as Euclidean distances, while the rotational distances are determined using the following formula:

$$d_{\mathrm{r}} = \mathrm{ang}(T_{\mathrm{mod}}, T_{\mathrm{meas}}),$$

where ang returns the rotation angle between the two matrices.

As the modeled transformation matrices depend on the model parameters, they change in each iteration of the optimization to be closer to the measured transformation matrices.

To get good initial values for DH parameters and joint angles, a preliminary optimization scheme is used in the beginning.

5) Initial joint angle values: Before the DH parameter optimization process, an initial procedure is executed to optimize the joint angles. Joint angles, at first all set to zero, are optimized using a simulated annealing procedure, keeping the DH parameters constant. This way a good approximate model posture is computed and the resulting joint angles are used in the further optimization process. Simulated annealing is used rather than a gradient-based method because it gives lower values of cost function (see Appendix C). Both methods are fast enough, as this optimization is only done in the initial phase, once for every subject.

6) Preliminary optimization: In the preliminary phase, the hand is divided into parts that are optimized separately. This way good initial values are computed fast because the chains are smaller, and also in this phase reference postures and base frame are not optimized. For the thumb a separate chain consists of the part from the MC1 to the PD1 marker, while for the rest of the fingers, chains from the PP to the PD markers represent separate parts to be optimized (Figure 2). The palm, the part without the fingers, is also optimized separately.

7) Main optimization cycle: The initial parameters computed in the preliminary optimization are further optimized in the main cycle. Here there is one cost function that is computed as a summation through all the markers and all the postures. Here the optimization of reference postures and the base frame is included. Reference postures consist of the transformation matrices of the markers. To minimize the number of parameters, the transformation matrices are not used directly, but the rotational part is converted to Euler angles. Base frame transformation matrices are optimized the same way and are initially equal to the forearm marker transformation matrices. Therefore the base frame positions and orientation are optimized separately for every posture. The main optimization cycle consists of two phases. In the beginning, a simulated annealing optimization procedure is used to avoid local minima. After this phase, the optimization is continued with a first order gradient-based procedure, which is faster than the simulated annealing, but more sensitive to local minima. The axes chains are displayed in Figure 3. The resulting performance turns out to be better than when using only a gradient-based optimization (see Appendix C).

C. Unified model

The final goal is to analyze the optimized individual hand models and investigate the possibility of creating a unified or generative model. First step in this analysis is the use of Principal Component Analysis (PCA) to examine the correlation between the DH parameters of the individual hands models and create a unified model. Vectors of DH parameters are first transformed using PCA to a new coordinate system whose bases are linear, mutually orthogonal, combinations of the DH parameters. The bases are computed as the eigenvectors of the covariance matrix of the DH parameters and ordered in decreasing order of the corresponding eigenvalues. The eigenvalues are equal to the variance of the DH parameters along the corresponding eigenvector. These transformed vectors of DH parameters are returned to the original parameter space, but using only a reduced number of eigenvectors. This way the number of parameters is reduced with least loss of information. The basic formula for computing transforming the data to a new parameter space using PCA is the following:

$$y_k = (x_k - \bar{x})E,$$

where x_k is a vector of original DH parameters, $\bar{x}$ is the mean of DH parameters for different subjects and the rotation matrix E represents a matrix that contains eigenvectors as columns. To return the values to the original parameter space, the following equation is used:

$$x_k = y_k E^{\mathrm{T}} + \bar{x}.$$

When returning the data to the original parameter space, a subset of eigenvectors can be used, to get a reduced number of parameters. If the eigenvectors corresponding to the lowest eigenvalues are set to zero, dimensionality is reduced with least loss of information. The average quadratic transformation error is equal to the sum of eigenvalues of omitted vectors [9]:

$$e = \frac{1}{n}\sum_{k=1}^{n}(x_k - x_k^{'})^2 = \sum_{i=q+1}^{p}\lambda_i,$$

where n is the number of data points, q is the resulting number of dimensions and λ_i are the eigenvalues. In this work the dimension reduction methods are used to generalize both static and dynamic parameters. It is executed on DH parameters for all subjects and joint angles for all postures

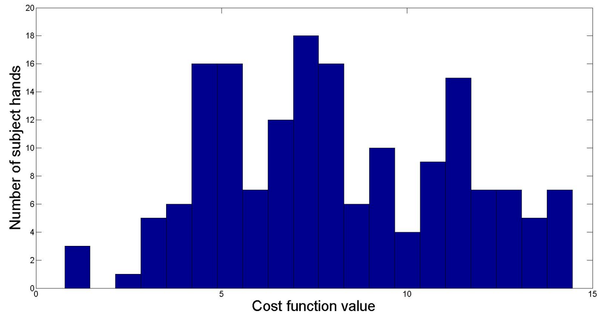

Figure 4: Distribution of cost function values at the end of the optimization procedure

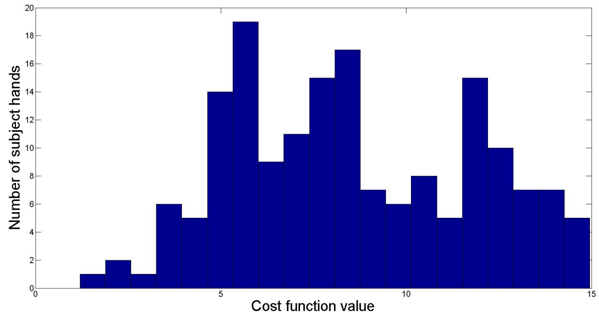

Figure 5: Distribution of mean cost function values after cross-validation

for different subjects. Generalization possibilities are examined also for both DH and joint angles together, to get a model with reduced dimensionality that would describe both axis parameters and synergies between joint angles.

III. Results

A. Individual models

Optimization of individual models of hand kinematics is executed in order to optimize the already described cost function. There are various values of cost functions achieved for different subjects, and the average value is 7.56 (Table 1). After the optimization a cross-validation procedure is executed to avoid overfitting. Inverse kinematics is computed for 10 randomly chosen time samples per subject to validate the previously optimized parameter values. Histograms in Figure 4 and Figure 5 show the distribution of cost function values for the measurement set used for optimization and mean values of cost function for the validation test, respectively.

B. Unified model

The tool used for dimension reduction in this work is PCA transformation. It is used on DH parameters and joint angles, both separately and together. Loss of information with dimension reduction on DH parameters is shown in Figure 6. One can notice that already 28 features describe 90% of the variance, while with 43 parameters the loss of information is 2%.

A similar procedure is done using joint angles separately. This is displayed in Figure 7. Here, however, to get 90% of information only five eigenvectors can be left out.

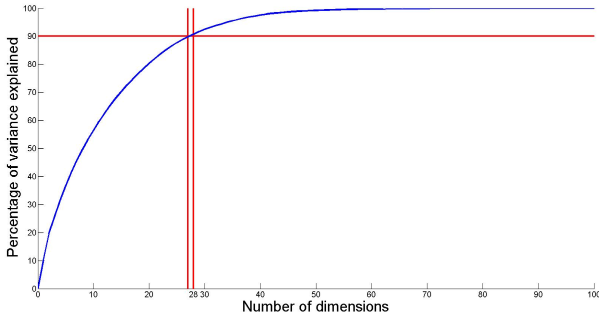

Figure 6: Results of PCA transformation on DH parameters

Using the DH parameters and joint angles with dimensionality separately reduced with PCA, another PCA transform was made. The separate reduction was done in a way to keep 90 % of the variance, for both DH parameters and joint angles. Its characteristics are shown in Figure 8. Already 14 dimensions describe 90% of the variance. To validate the model, errors were computed for 10 randomly chosen samples from every subject. Mean and standard deviation of cost function values achieved using this parameter set are shown in

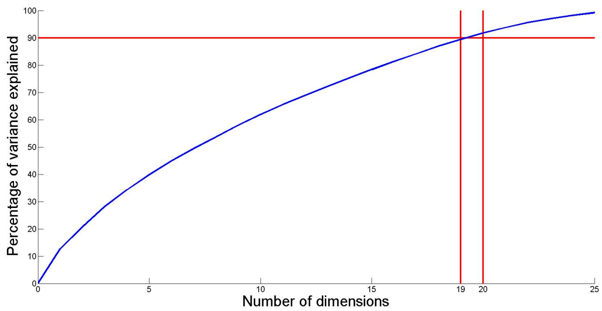

Figure 7: Results of PCA transformation on joint angles

Table 1. Cost function values for different test cases

Description	Mean	St.Dev.	Static dimensions	Dynamic dimensions
Optimization	7.56	5.72	104	26
Cross-validation	8.77	5.93	104	26
PCA on DH	9.53	3.29	28	26
PCA on joint angles	9.22	5.23	104	20
Description	Mean	St.Dev.	Dimensions	
PCA on reduced DH and reduced j.a.	11.46	5.51	14	
PCA on original DH and original j.a.	10.56	6.28	27	

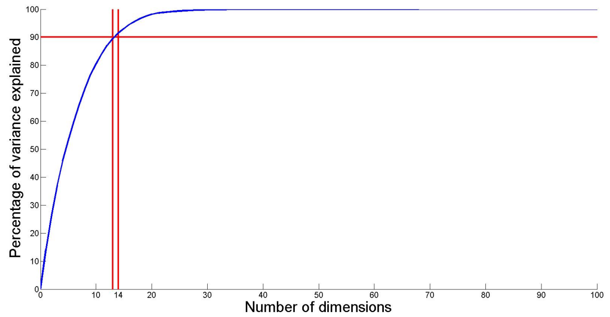

Figure 8: Results of PCA transformation on reduced DH and joint angle parameters together

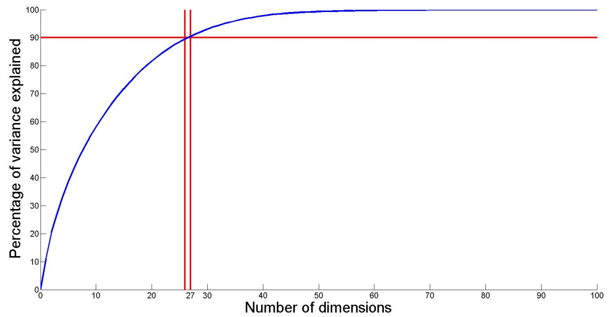

Figure 9: Results of PCA transformation on original DH and joint angle parameters together

Table 1.

For comparison, a PCA transform on original DH and joint angle parameters together was made as well. Figure 9 shows its performance. One can notice that here more dimensions are needed to explain the same percent of variance because original DH parameters and joint angles carry more information.

IV. Conclusion and Future Work

Results show that dimension reduction with PCA transformation could give a good generalized model of human hand kinematics. The graphs of PCA transformation results (Figures 6-9) show that large amount of variance in static and dynamic parameters, both together and separately can be explained by a small number of principal components. This is the consequence of high correlation between different parameters for different subject hands. PCA does not generalize well only on joint angles. This can be explained by great variation in hand postures used in the measurements. There is no paper currently known to the author that gives a generalized model for both static and dynamic parameters. A problem with the generalization of the DH parameters is a relatively small number of subjects compared to the number of parameters, even though both left and right hands are used together in the PCA transformation. Another problem can be that the DH parameters contain the axes positions and orientation relative to parent axes. This means that loss of information in one parameter affects all the child axes and segments. For example, change in the wrist axis would practically influence the whole hand. Therefore, possibly a good alternative is to generalize link positions and orientations instead of axes parameters. Results of dimension reduction might be improved by exploring different configurations of deep autoencoders, to reveal nonlinear dependencies between parameters. This way intrinsic dimensionality could potentially be further reduced for the same loss of information.

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Appendix A: Picture of tetrahedron markers

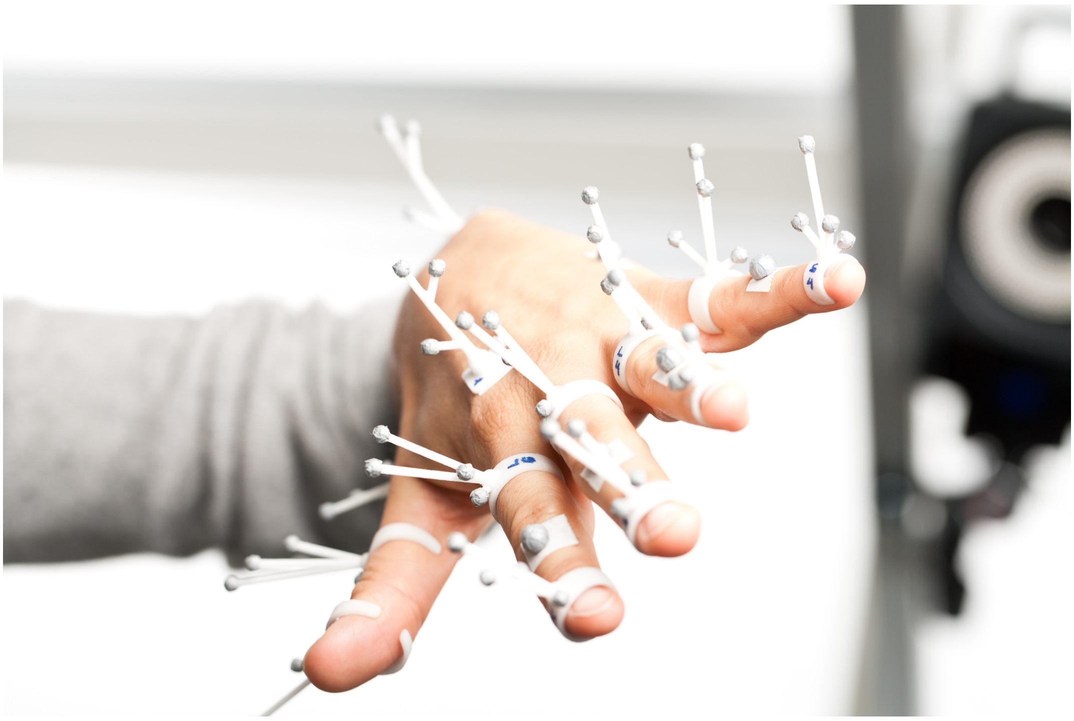

Figure 10: Picture of a hand with tetrahedron markers on the segments. Taken by Holger Urbanek, DLR.

Appendix B: Custom templates determination

Custom templates are determined when the marker size is not available and it is not possible to determine the origin of the marker, i.e. the point closest to the segment itself.

The steps are the following:

1. Determine the median distances between markers in a markerstar, throughout time samples and scan recordings.
2. Find the time sample where the distances are closest to the median (best sample).
3. Construct a new tetrahedron in the following way:

a) Position of the first marker is equal to the position of the first marker in the best sample.

b) Position of the second marker is set along the direction between the first and the second marker of the best sample, with the median distance taken as the distance between the first and the second marker.

c) Third marker is set as a vertex in a triangle.

d) Fourth marker is set as an intersection of the three spheres, defined by previous three markers and the median distances to the fourth marker.

This new tetrahedron is used as a template. It can be used in two ways:

1. Transformation matrix is approximated between the four markers of the custom template and all the existing templates. When the least squares error of approximation of at least one of the transformation matrices is below a threshold, the existing template with the lowest error is taken as template for this marker star.
2. If in step 1 no suitable transformation matrix is found, median position of the markers in the custom template marker star is taken as the origin of the marker. Since only the relative position and orientation change is relevant to the algorithm, this is a good approximation.

Appendix C: Test of optimization algorithms performance

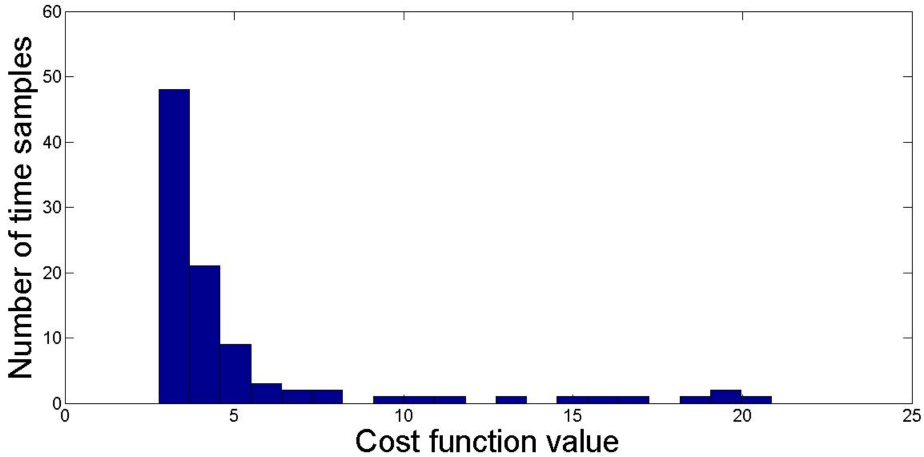

Figure 11: Example of distribution of cost function values for one hand after preliminary optimization with simulated annealing

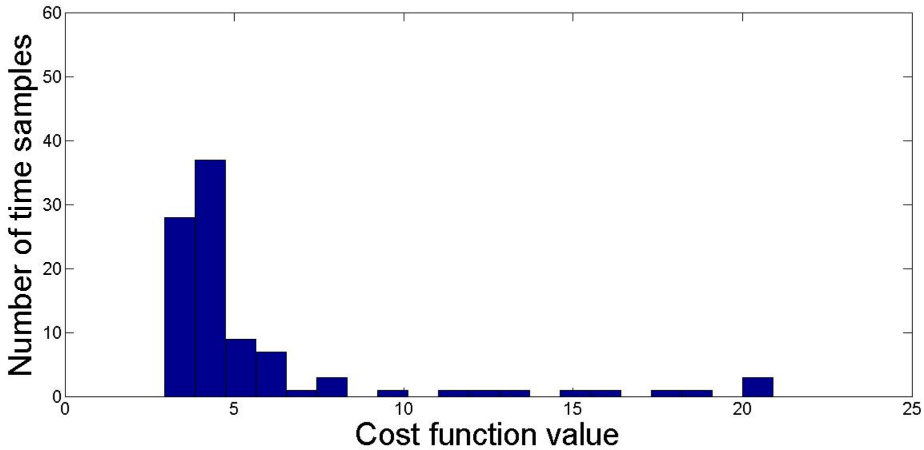

Figure 12: Example of distribution of cost function values for one hand after preliminary optimization with a gradient-based algorithm

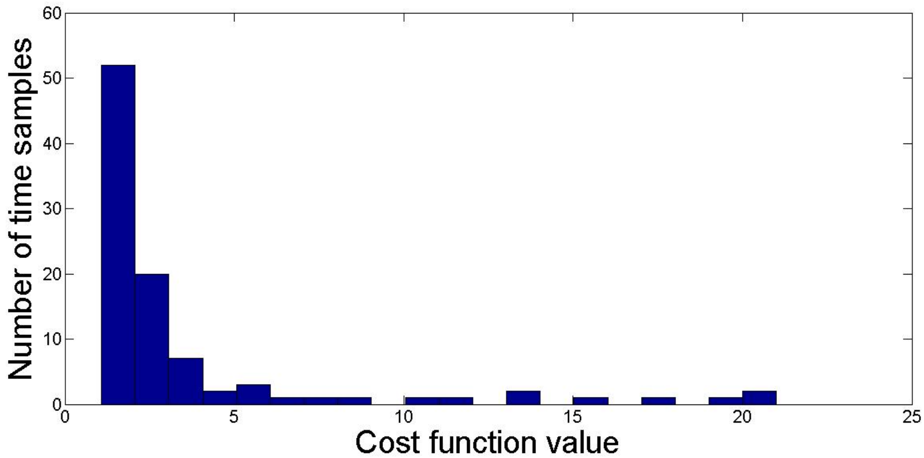

Figure 13: Example of distribution of cost function values for one hand after main optimization cycle with simulated annealing

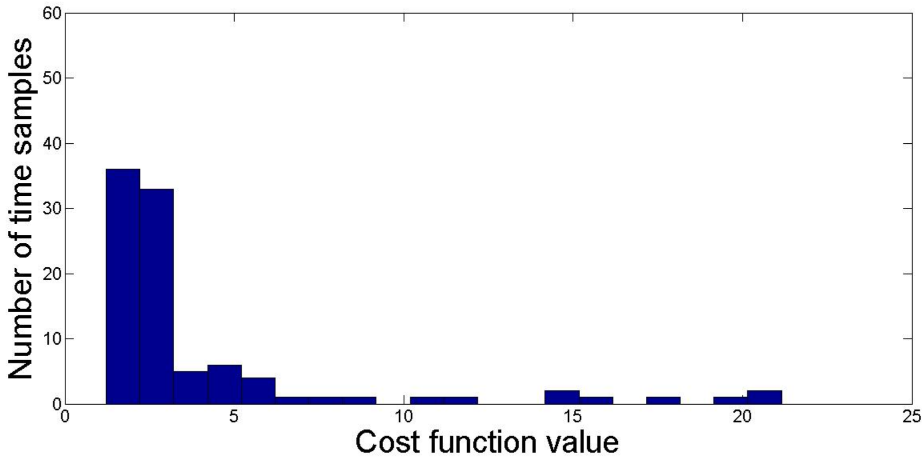

Figure 14: Example of distribution of cost function values for one hand after main optimization cycle with a gradient-based algorithm

Appendix D: DH parameter values through different levels of dimensionality reduction

Table 2. DH parameter values for a chosen subject hand, with full dimensionality

d [mm]	θ [rad]	a [mm]	α [rad]
-0.42	0.01	-42.07	0.79
12.28	-3.14	1.19	-1.57
-1.26	-1.57	16.18	-1.58
18.37	1.57	-10.38	1.61
51.37	-1.59	1.93	1.57
-11.68	3.12	27.90	1.58
-18.43	-3.12	0.40	1.55
0.00	-0.09	-32.23	-0.04
65.01	-1.56	5.20	-1.54
12.56	1.57	-0.22	1.60
-0.03	3.14	45.59	-0.11
-0.02	-0.03	26.43	-0.02
20.08	-3.13	-67.78	-1.58
9.31	3.12	0.84	-1.62
-0.02	-3.11	-46.60	0.06
0.01	0.03	-28.07	0.02
12.79	1.57	4.87	1.57
61.35	1.57	12.84	-1.56
-5.45	1.57	-1.29	1.58
0.00	3.12	47.16	-0.03
0.01	-3.11	-26.44	0.01
25.97	-1.58	-21.61	-1.58
50.44	1.57	-13.25	1.54
-6.01	1.58	0.61	-1.58
-0.03	-0.08	36.08	-0.05
-0.01	0.05	19.75	-0.01

Table 3. DH parameter values for a chosen subject hand, taking only one dimension into account

d [mm]	θ [rad]	a [mm]	α [rad]
-0.42	-0.00	-1.71	0.75
8.65	0.02	1.79	0.18
9.02	-0.28	13.66	-0.05
0.43	0.16	-14.94	0.99
22.78	-0.32	2.31	0.39
-1.71	-0.01	13.32	0.01
-3.31	-0.01	1.99	0.26
0.01	0.07	-2.79	-0.01
3.61	0.07	4.89	-0.95
3.72	0.46	1.24	0.43
-0.01	-0.50	3.63	-0.02
-0.00	0.06	1.49	-0.00
3.21	-0.08	1.68	-1.06
0.88	-0.29	-0.06	-1.03
0.00	-0.23	5.87	0.02
0.00	0.03	1.11	0.00
-2.12	0.26	12.34	0.26
3.76	0.22	6.00	0.15
-1.32	-0.08	0.01	0.94
0.01	-0.09	2.09	-0.02
-0.00	0.21	2.76	0.01
-5.64	0.29	2.08	0.18
3.80	-0.03	0.08	0.92
-2.94	1.23	0.12	-0.92
0.00	0.12	19.72	-0.01
0.00	-0.32	-0.61	0.01

Table 4. DH parameter values for a chosen subject hand, taking two dimensions into account

d [mm]	θ [rad]	a [mm]	α [rad]
-0.42	0.01	-1.71	0.75
8.65	0.02	1.79	0.18
9.02	-0.28	13.66	-0.05
0.43	0.16	-14.94	0.99
22.78	-0.32	2.31	0.39
-1.71	-0.01	13.32	0.01
-3.31	-0.01	1.99	0.26
0.01	0.07	-2.79	-0.01
3.61	0.07	4.89	-0.95
3.72	0.46	1.24	0.43
-0.01	-0.50	3.63	-0.02
-0.00	0.06	1.49	-0.00
3.21	-0.08	1.68	-1.06
0.88	-0.29	-0.06	-1.03
0.00	-0.23	5.87	0.02
0.00	0.03	1.11	0.00
-2.12	0.26	12.34	0.26
3.76	0.22	6.00	0.15
-1.32	-0.08	0.01	0.94
0.01	-0.09	2.09	-0.02
-0.00	0.21	2.76	0.01
-5.64	0.29	2.08	0.18
3.80	-0.03	0.08	0.92
-2.94	1.23	0.12	-0.92
0.00	0.12	19.72	-0.01
0.00	-0.32	-0.61	0.01

Table 5. DH parameter values for a chosen subject hand, taking five dimensions into account

d [mm]	θ [rad]	a [mm]	α [rad]
-0.42	0.01	-42.07	0.79
12.28	0.02	1.79	0.18
9.02	-0.28	13.66	-0.05
0.43	0.16	-14.94	0.99
22.78	-0.32	2.31	0.39
-1.71	-0.01	13.32	0.01
-3.31	-0.01	1.99	0.26
0.01	0.07	-2.79	-0.01
3.61	0.07	4.89	-0.95
3.72	0.46	1.24	0.43
-0.01	-0.50	3.63	-0.02
-0.00	0.06	1.49	-0.00
3.21	-0.08	1.68	-1.06
0.88	-0.29	-0.06	-1.03
0.00	-0.23	5.87	0.02
0.00	0.03	1.11	0.00
-2.12	0.26	12.34	0.26
3.76	0.22	6.00	0.15
-1.32	-0.08	0.01	0.94
0.01	-0.09	2.09	-0.02
-0.00	0.21	2.76	0.01
-5.64	0.29	2.08	0.18
3.80	-0.03	0.08	0.92
-2.94	1.23	0.12	-0.92
0.00	0.12	19.72	-0.01
0.00	-0.32	-0.61	0.01

Table 6. DH parameter values for a chosen subject hand, taking 28 dimensions into account (corresponding to 90 % of variance explained

d [mm]	θ [rad]	a [mm]	α [rad]
-0.42	0.01	-42.07	0.79
12.28	-3.14	1.19	-1.57
-1.26	-1.57	16.18	-1.58
18.37	1.57	-10.38	1.61
51.37	-1.59	1.93	1.57
-11.68	3.12	27.90	1.58
-18.43	-3.12	0.40	1.55
0.01	0.07	-2.79	-0.01
3.61	0.07	4.89	-0.95
3.72	0.46	1.24	0.43
-0.01	-0.50	3.63	-0.02
-0.00	0.06	1.49	-0.00
3.21	-0.08	1.68	-1.06
0.88	-0.29	-0.06	-1.03
0.00	-0.23	5.87	0.02
0.00	0.03	1.11	0.00
-2.12	0.26	12.34	0.26
3.76	0.22	6.00	0.15
-1.32	-0.08	0.01	0.94
0.01	-0.09	2.09	-0.02
-0.00	0.21	2.76	0.01
-5.64	0.29	2.08	0.18
3.80	-0.03	0.08	0.92
-2.94	1.23	0.12	-0.92
0.00	0.12	19.72	-0.01
0.00	-0.32	-0.61	0.01

Table 7. DH parameter values for a chosen subject hand, using 43 dimensions (corresponding to 98 % variance explained)

d [mm]	θ [rad]	a [mm]	α [rad]
-0.42	0.01	-42.07	0.79
12.28	-3.14	1.19	-1.57
-1.26	-1.57	16.18	-1.58
18.37	1.57	-10.38	1.61
51.37	-1.59	1.93	1.57
-11.68	3.12	27.90	1.58
-18.43	-3.12	0.40	1.55
0.00	-0.09	-32.23	-0.04
65.01	-1.56	5.20	-1.54
12.56	1.57	-0.22	1.60
-0.03	3.14	45.59	-0.02
-0.00	0.06	1.49	-0.00
3.21	-0.08	1.68	-1.06
0.88	-0.29	-0.06	-1.03
0.00	-0.23	5.87	0.02
0.00	0.03	1.11	0.00
-2.12	0.26	12.34	0.26
3.76	0.22	6.00	0.15
-1.32	-0.08	0.01	0.94
0.01	-0.09	2.09	-0.02
-0.00	0.21	2.76	0.01
-5.64	0.29	2.08	0.18
3.80	-0.03	0.08	0.92
-2.94	1.23	0.12	-0.92
0.00	0.12	19.72	-0.01
0.00	-0.32	-0.61	0.01

Appendix E: Principal Components Illustration

Table 8. DH parameters of chosen subjects (each row corresponds to a different subject) mapped by PCA transformation, Part 1

-161.44	-186.68	26.45	-83.00	165.45	15.83	-88.16	-54.54	-33.89	-147.62	-0.87	139.90	-25.45	40.94	-79.85
23.84	-206.03	102.59	-249.36	34.12	0.96	-52.25	82.61	-14.23	-71.39	79.35	44.28	19.89	46.40	-7.78
-366.23	-68.99	172.88	-30.87	185.80	-26.98	-219.64	-105.59	35.49	-136.41	-99.88	0.66	111.00	25.58	-138.71
155.96	31.55	146.48	42.76	-66.44	136.29	111.66	-83.03	-79.57	-157.07	-63.69	31.60	54.32	-193.23	-141.92
-189.03	259.27	263.54	-153.31	245.84	-65.24	-9.24	55.03	-259.31	-5.09	-25.34	49.99	2.17	-56.54	20.10
-159.16	265.40	206.07	-128.84	324.07	92.60	5.68	-48.63	-223.23	-45.10	187.10	28.31	62.60	-24.15	-63.03
12.38	138.07	144.14	31.85	-359.38	48.12	-63.48	-9.72	-37.91	115.58	86.18	188.13	202.69	-157.12	28.41
45.95	15.90	116.35	57.45	-215.04	58.81	206.32	-45.71	-131.45	-19.84	20.03	212.77	102.17	-189.62	200.31
-75.59	-108.84	-75.69	144.40	-197.65	232.56	-219.06	68.70	-76.78	76.83	66.72	182.39	-9.06	-99.65	-93.31
328.33	-40.75	100.98	-83.24	-65.80	116.45	-190.73	26.39	-51.47	-50.43	-104.45	-318.59	123.88	78.88	90.96
-113.16	-60.54	82.35	-175.14	122.76	-178.68	-191.72	115.48	-85.04	-31.07	-19.98	-16.17	-105.89	-99.81	-49.38
-394.30	-268.02	-119.96	3.52	-55.97	12.46	124.69	0.06	-217.21	-52.47	55.68	-43.53	-111.30	-5.82	-56.40
-378.42	-168.20	15.89	-26.71	-13.63	-224.37	-0.24	41.01	17.30	-62.89	-42.39	198.13	-83.82	-106.40	-3.28
-67.39	260.79	94.12	-206.22	132.24	122.27	95.30	220.64	73.43	-101.19	70.98	-140.13	70.39	111.72	-133.02
-391.14	153.19	6.94	162.18	271.55	119.45	31.51	71.57	-126.72	57.50	57.20	-117.90	12.00	30.52	-71.94
-54.26	134.13	160.37	-132.41	-196.60	-256.54	-130.46	48.42	-117.96	34.55	32.94	107.39	116.93	102.97	145.93
19.75	180.01	37.67	285.55	215.79	-136.69	-95.56	-11.21	-59.61	-38.78	248.98	173.75	131.03	-58.81	8.98
-22.79	130.36	154.59	-233.21	-83.61	-198.32	-259.19	90.81	54.48	116.96	91.93	-73.19	70.98	-39.63	90.61
-394.04	-170.38	124.74	94.45	123.48	121.64	86.67	105.31	52.48	86.36	-8.04	-45.72	-155.12	71.06	-20.82
-116.77	-286.90	-137.89	272.44	-262.16	-104.19	107.27	-34.44	-146.89	27.81	29.34	-8.77	30.79	-84.25	91.88
88.87	240.48	237.64	-59.91	-137.99	-271.00	-95.07	290.18	126.52	-138.82	-16.62	109.76	-3.47	-26.22	89.49
-24.03	-264.06	37.46	156.47	-336.75	79.39	-279.15	-110.98	-109.98	98.10	60.21	41.13	-55.71	-71.62	-55.28
282.24	-218.86	85.93	-324.82	202.01	12.17	-20.37	97.47	70.50	-100.24	10.64	-62.75	-63.98	8.32	-14.31
-16.59	26.75	-218.12	-30.75	80.10	-8.08	-288.71	121.99	-212.57	-50.03	104.66	39.70	98.12	140.68	-1.20
-144.98	-242.36	-208.81	137.60	-269.75	-263.27	136.03	202.68	27.36	-159.98	125.76	37.39	32.03	25.75	0.43
25.44	10.58	-57.38	-220.94	-155.64	-169.40	-194.28	293.89	40.67	90.08	-24.19	57.15	15.67	59.34	-76.13
279.72	-237.09	-3.92	236.40	284.83	202.43	36.09	-77.96	47.64	-19.55	159.03	75.34	-1.30	-23.17	-158.41
57.57	0.68	-113.76	349.81	-38.34	79.89	42.32	59.94	-99.09	-1.57	-24.99	-180.13	138.73	-111.11	-45.13
-84.75	-25.67	-42.67	159.06	-125.99	318.86	-270.84	-112.01	-219.93	40.99	106.06	62.02	-196.61	-39.14	-4.21
402.87	-243.01	67.20	-91.75	190.96	126.27	58.12	-104.30	-15.71	-100.02	164.10	14.46	139.86	37.22	-178.13
-373.83	16.89	236.86	205.72	97.73	-140.66	32.96	50.22	156.25	142.80	-132.02	-51.51	55.97	116.72	91.80
-410.18	44.04	280.14	209.46	97.00	-105.27	33.95	-22.67	158.31	77.34	-73.41	-13.27	103.79	85.91	-5.54
-410.18	44.04	280.14	209.46	97.00	-105.27	33.95	-22.67	158.31	77.34	-73.41	-13.27	103.79	85.91	-5.54
-157.93	-340.82	-230.01	-19.59	-70.50	243.95	130.26	167.72	66.90	-16.73	-112.02	0.93	240.38	3.63	-41.96
-396.00	-41.11	21.14	103.95	72.96	39.83	115.69	163.61	-40.37	62.74	-0.27	-45.55	-216.22	-14.72	-86.27
-184.90	-406.89	2.16	51.72	-35.88	-31.46	-123.10	-43.09	-72.29	-154.99	166.20	-17.23	-79.62	-79.13	-14.49
-248.11	-257.15	154.88	-246.31	-53.34	53.11	148.06	-64.26	-99.01	-68.19	110.78	-130.73	40.05	87.07	-64.04
-172.08	-336.82	-195.50	30.57	-148.04	239.57	126.10	84.82	-0.72	-108.74	-165.11	-4.34	117.01	77.17	20.67
-200.36	42.52	26.13	337.83	2.04	-73.37	-3.54	52.24	-183.58	11.68	115.76	-209.13	-52.54	28.69	-10.91
180.72	72.91	12.64	371.42	-145.55	-27.22	-39.36	150.02	-25.56	129.26	-147.70	-187.10	-15.89	-22.84	-26.59

Table 9. DH parameters of chosen subjects mapped by PCA transformation, Part 2

-37.90	23.89	-79.94	114.92	-19.07	109.93	112.20	171.80	88.03	-113.39	-66.98	5.52	35.04	2.96	36.63
73.29	-140.27	53.54	-88.70	96.03	-82.03	48.93	175.66	99.84	-86.61	-6.00	16.21	101.73	6.79	3.37
39.24	-19.98	-73.51	21.73	-32.59	23.00	65.77	78.64	81.07	-5.21	-11.57	-17.97	41.14	-3.16	14.83
-34.66	153.53	-38.44	-171.89	136.07	-60.71	44.76	-74.95	-4.84	-34.06	7.08	105.34	-47.48	-10.20	-16.98
-17.43	-129.97	81.04	-6.13	31.20	41.79	10.40	-119.75	-88.67	44.74	29.45	-27.84	-12.67	-21.17	17.00
81.77	9.62	-3.07	-1.56	-45.34	-18.21	-19.74	-39.76	21.49	-28.14	-15.71	-26.54	39.68	-38.31	-52.11
-81.78	136.42	-69.69	-108.98	98.96	-68.07	12.61	-19.23	1.39	-61.32	17.61	73.09	-16.79	-28.36	67.98
54.00	-142.45	-38.68	-6.84	-51.61	49.22	-32.99	5.81	60.97	-34.99	46.30	47.45	27.32	-22.91	-97.27
-108.87	126.82	-68.48	-64.50	172.20	-59.66	27.80	4.69	55.25	-36.96	-1.69	43.23	-75.00	-88.59	137.03
155.90	78.07	-38.22	35.82	-50.73	-1.09	89.69	14.48	-42.08	-29.05	-0.75	51.20	61.22	37.79	64.28
-15.57	-40.78	-30.04	-35.96	76.82	-60.57	63.31	4.06	67.55	-73.89	56.64	91.21	-25.08	53.27	-9.04
119.07	8.52	55.11	-36.14	-116.27	27.29	-67.58	-8.40	-36.31	-5.08	29.19	-32.00	-2.35	27.54	68.71
-50.02	-12.33	-191.66	-65.98	13.38	-27.75	-134.22	90.50	66.20	-6.85	87.08	12.29	25.37	8.47	-43.78
-112.05	183.24	-91.36	-33.12	-36.72	-45.38	67.12	-1.65	-7.17	-31.56	-100.79	14.10	22.98	31.35	30.72
95.32	54.35	32.98	-166.18	-73.14	68.65	-115.94	-72.06	-53.25	25.45	11.38	-14.61	8.94	17.37	-13.14
8.31	-51.66	162.04	12.34	-30.19	98.93	-191.25	12.50	-38.79	-69.06	-12.16	4.58	4.37	-20.02	7.09
101.57	46.57	27.53	41.76	-121.45	11.43	91.27	-13.12	60.28	-20.13	-108.99	51.62	57.23	-41.12	-2.80
-163.43	41.15	40.96	-57.14	-80.52	-110.37	-220.40	-32.59	-29.13	20.44	-0.36	-18.52	15.01	20.31	13.07
-27.93	-32.87	-75.52	-117.49	62.49	86.95	-6.45	-4.68	-6.77	-73.78	-46.02	4.69	-61.67	22.61	-14.52
178.81	-125.30	-90.03	56.88	-99.93	-17.24	-133.75	-99.20	-28.72	5.22	44.37	7.19	4.71	8.23	21.85
-26.14	-59.89	-30.41	-106.84	33.50	-80.79	148.62	-43.60	21.71	38.00	-37.47	66.91	7.33	-10.27	18.26
70.61	21.83	-121.09	1.98	15.19	100.83	49.29	-3.73	27.75	16.04	-67.02	-115.78	-2.81	-86.07	-71.05
7.01	4.36	120.77	-83.33	-123.95	-13.76	-144.41	-54.62	15.18	-16.54	-68.70	6.54	-5.05	33.75	44.08
-23.65	127.44	339.98	91.49	-37.73	77.81	-170.82	31.95	-23.48	41.97	-101.91	33.03	7.13	-29.38	18.15
5.55	40.63	-48.15	-83.81	11.63	-0.10	19.53	-1.26	11.43	22.13	-38.58	80.27	-1.60	-14.67	0.37
-191.69	6.58	131.64	-0.08	8.63	98.04	-112.21	20.48	120.57	-5.16	-77.84	-39.68	-9.26	32.46	-45.41
-40.68	10.81	25.72	-41.79	5.79	27.03	-10.24	-16.46	-23.53	-62.47	-69.46	50.47	-63.30	-32.44	-86.68
-217.88	-36.32	-44.97	-48.06	74.55	30.28	-11.18	-62.22	25.15	56.57	-31.47	103.26	-1.86	-8.98	60.22
78.65	136.92	-57.90	28.21	-6.31	2.85	-57.59	-17.96	-67.79	-15.58	-77.17	-71.08	-9.48	-42.98	22.05
53.92	-28.98	-86.93	-52.13	15.46	13.82	-118.73	0.83	-22.03	-56.16	-15.16	66.21	-1.10	-27.77	-33.73
-7.86	-3.41	77.34	-100.85	59.53	-61.15	20.80	60.85	-86.18	-80.55	3.58	-81.49	44.26	49.34	-33.78
2.61	85.34	-76.35	19.39	-11.35	9.10	96.99	-19.16	-21.74	-84.87	-73.38	-39.12	-20.53	24.38	39.32
2.61	85.34	-76.35	19.39	-11.35	9.10	96.99	-19.16	-21.74	-84.87	-73.38	-39.12	-20.53	24.38	39.32
-72.82	-46.65	63.71	38.99	-29.65	34.33	-30.79	-70.27	-12.47	84.14	-6.06	23.15	-27.04	53.57	56.38
-87.15	28.22	-137.72	-149.95	41.46	9.41	-61.82	14.58	12.94	-88.30	28.84	33.24	-58.15	6.22	-11.35
59.96	-151.23	26.09	-67.28	33.63	-8.42	55.32	4.48	84.32	70.95	-55.96	53.27	14.25	-35.44	-51.65
60.96	38.06	-39.92	78.77	8.41	-65.01	97.85	-30.64	-28.66	-66.99	-51.28	-27.93	-25.13	-10.01	51.45
-15.13	23.33	28.79	52.99	20.96	83.92	-14.22	20.09	-14.51	21.73	7.93	7.47	-21.52	29.95	-24.48
144.41	-103.75	247.05	-135.97	-40.49	-115.38	88.66	-30.83	-54.89	-15.45	-20.57	-37.53	41.25	-13.97	5.58
-22.59	61.79	31.15	-50.59	-11.01	-105.09	69.27	129.08	108.66	-57.11	14.10	-69.26	95.14	7.54	-64.32

Table 10. DH parameters of chosen subjects mapped by PCA transformation, Part 3

-18.81	-41.41	-0.76	75.50	35.21	-6.75	-54.98	-68.43	16.11	21.19	13.42	3.92	9.88	-61.41	-7.03
38.19	-36.24	-11.75	138.50	-40.68	-40.01	-67.00	-55.40	-42.47	-11.61	74.54	-15.31	15.88	-49.34	-44.22
-0.58	-7.43	2.07	24.96	6.27	1.93	11.24	-4.29	-23.60	-26.56	13.09	-3.19	-12.02	24.74	1.24
99.23	26.13	-38.28	60.90	-106.95	-105.68	67.46	-109.99	11.91	-65.08	19.93	22.08	23.25	-16.99	6.99
8.55	-22.56	30.46	47.67	-4.78	-22.41	22.08	-3.94	-18.70	34.80	-32.15	19.99	-29.96	17.82	-19.27
-11.71	-26.10	8.53	-58.05	22.12	8.52	-8.57	40.34	19.40	50.24	-38.47	32.75	9.00	26.20	4.94
19.03	10.81	20.81	60.33	-14.73	-67.39	-16.15	-9.62	-1.48	-20.22	-2.57	7.74	8.32	2.67	14.91
38.24	-43.90	-37.69	56.38	-22.65	-33.11	-61.29	-17.88	2.34	20.11	29.01	16.73	28.00	11.42	-55.86
19.58	-29.96	37.37	83.62	87.17	21.42	-64.19	21.33	-83.41	-25.41	-53.10	-8.90	27.62	31.26	8.33
15.68	-54.11	-26.97	-12.48	-55.38	0.11	-58.47	44.63	18.32	25.33	-14.22	-20.65	1.95	12.14	7.97
19.11	37.51	81.31	-102.04	-7.18	12.11	25.52	34.96	6.55	-42.86	-56.11	62.38	70.80	24.65	2.56
-30.74	15.28	7.29	46.89	-7.60	9.46	-26.35	12.41	15.21	-3.80	2.97	-2.30	-14.70	3.85	10.64
-34.04	39.98	-26.38	3.52	-22.60	-13.05	-23.64	39.69	8.50	13.28	27.17	2.50	-18.33	6.76	-6.77
-29.60	78.73	-11.99	-92.45	-35.81	-4.11	57.37	-49.49	63.75	-19.70	2.38	-16.23	-53.30	-20.67	-34.38
-60.82	14.16	-88.97	18.32	-27.72	-39.78	-44.32	92.88	-0.29	21.46	24.02	3.80	2.70	29.28	6.35
66.89	-37.28	-29.14	-50.97	-5.70	13.42	43.06	44.36	15.60	58.43	-44.86	14.69	-1.64	-12.79	-5.63
-76.92	-9.74	4.71	18.58	45.48	-42.39	-86.71	-1.85	59.01	39.29	24.04	-12.55	16.54	-33.65	-3.57
36.76	13.49	-4.97	-72.61	19.15	-17.44	-11.74	64.52	10.51	17.47	-4.65	-9.47	-3.43	20.61	3.13
-2.93	-9.21	-95.88	-6.56	-6.58	-5.10	-0.34	36.15	0.45	40.71	-1.37	-1.39	8.91	-15.49	-1.53
16.85	5.37	19.94	-53.77	-22.21	27.27	24.63	26.98	4.57	27.88	11.63	25.10	-11.02	5.29	3.78
-16.14	19.35	55.68	-56.84	-2.14	37.40	43.02	-22.13	-20.71	6.25	-21.60	-16.37	-0.06	19.02	-27.16
21.98	74.09	0.09	35.08	28.60	-66.27	3.02	4.55	-35.57	-23.88	6.60	5.00	-27.34	44.01	-19.74
63.35	-22.11	-40.06	36.10	2.57	6.65	-33.97	-31.42	-44.40	50.54	-5.24	-36.61	19.73	-11.15	10.29
14.98	39.72	-94.42	-66.78	-32.14	-30.28	62.76	2.09	50.00	29.77	-6.70	-24.30	-3.31	0.84	-38.05
-28.05	42.98	21.33	-42.97	-12.14	39.68	-0.40	32.39	9.83	-7.65	14.77	-7.47	-15.27	6.04	-8.96
-0.61	87.00	22.99	-111.10	65.75	28.81	5.95	-6.08	-41.19	-25.03	-1.78	36.19	34.64	8.43	-17.38
29.77	-19.33	23.67	-68.48	43.74	25.29	22.22	20.78	-3.99	-5.21	11.90	0.78	35.04	-14.11	18.65
-8.01	-38.50	-20.14	48.15	-14.04	-19.69	-75.62	9.69	19.12	16.65	21.62	22.05	-4.92	-37.55	-42.96
30.71	120.58	-67.23	5.65	-64.62	-95.41	59.76	-33.87	35.23	-33.07	26.13	1.66	-4.74	24.30	-4.01
25.20	-35.60	1.63	-26.49	-17.37	18.79	-4.66	33.21	-6.72	-4.89	19.88	9.57	8.87	-0.73	14.42
4.42	34.53	-13.79	39.17	3.12	-12.54	23.58	28.02	7.70	17.38	-11.76	-29.45	12.13	-30.31	-14.51
8.05	4.72	6.57	-12.49	23.65	8.22	19.43	8.16	4.76	4.52	-1.09	-33.00	9.52	20.89	4.69
8.05	4.72	6.57	-12.49	23.65	8.22	19.43	8.16	4.76	4.52	-1.09	-33.00	9.52	20.89	4.69
-59.09	3.88	2.12	-15.68	27.53	8.61	31.94	-43.80	-8.33	-11.02	1.98	9.81	-0.13	-40.86	-5.39
14.71	-6.24	-54.05	-0.06	-19.27	20.52	-9.67	37.86	5.56	2.80	9.22	7.11	16.09	0.37	0.17
-2.03	-5.40	-25.37	-12.57	2.64	-26.31	-35.55	23.82	-1.35	-4.03	4.73	-10.43	-15.10	-1.21	-17.61
75.22	-33.72	59.84	-13.12	15.45	41.89	-2.00	-21.42	-6.78	-18.34	-3.82	-5.65	7.77	7.41	26.26
-10.40	-21.54	-36.00	-62.90	-2.14	50.08	34.51	2.19	-0.70	11.09	-30.01	7.85	-8.21	-14.28	13.11
43.98	10.31	49.82	56.36	2.22	39.54	30.85	4.98	-17.96	-28.11	-8.32	-1.77	19.08	-2.28	-16.32
-9.84	5.87	-0.80	5.84	16.19	30.09	-29.69	-3.84	38.05	1.20	-7.68	-18.37	-4.50	-60.13	-12.51

Table 11. DH parameters of chosen subjects mapped by PCA transformation, Part 4

32.44	7.38	7.88	17.49	55.33	1.17	-22.63	-8.40	19.39	-7.09	-12.58	3.63	26.83	-6.99	-4.17
21.56	-11.03	52.35	22.57	10.34	-11.41	-1.16	-20.99	5.62	-19.65	1.13	-6.77	10.82	13.12	-9.21
-4.19	15.42	25.35	-18.06	-6.82	-5.63	27.59	7.49	-2.60	10.54	-14.03	-16.47	-9.48	-5.40	6.67
-12.37	-15.07	10.54	27.70	13.12	22.62	-15.68	0.29	18.80	-16.01	13.30	-23.07	9.56	-6.20	2.43
21.85	22.73	27.99	-16.38	5.04	-7.77	2.80	5.49	5.85	-1.79	3.79	-17.64	10.78	9.29	2.95
55.58	38.54	-15.65	6.31	39.11	-22.43	-25.09	9.92	38.81	4.79	0.30	-5.23	1.94	20.98	-15.95
-29.28	-13.59	-8.32	-6.43	5.29	12.42	9.21	-6.60	-1.82	-3.21	-13.45	-11.88	-13.38	-8.73	-8.66
-3.30	-60.35	19.95	-0.60	-17.30	35.29	23.67	27.01	-6.04	20.81	-5.91	13.01	-4.32	-2.07	20.92
51.52	-26.44	8.05	-40.41	-8.54	36.51	3.15	-4.49	20.79	-21.66	18.73	10.28	11.40	19.96	-3.43
-23.93	-16.25	3.46	17.80	-9.76	11.13	-8.06	0.94	19.86	-6.85	-2.06	-5.50	-2.93	2.15	3.55
45.73	9.68	-16.79	8.74	9.76	26.63	-18.75	11.00	-43.35	-32.38	27.54	-10.61	5.76	9.82	-1.00
-18.48	9.57	-8.92	0.05	4.37	-4.30	8.51	14.11	-7.98	-6.95	1.56	6.95	-6.98	-4.08	-12.33
-2.91	4.55	-14.96	13.69	-10.44	-16.01	14.03	-20.15	16.24	-8.25	5.18	-14.54	-7.12	13.61	-9.77
48.73	37.49	-2.88	1.75	-12.05	7.46	-6.87	18.78	32.64	8.64	-14.42	-1.40	-3.18	1.33	3.12
-5.27	-30.50	31.18	-1.46	-10.60	-7.31	5.56	7.31	-9.36	10.38	-6.33	5.79	6.12	-22.53	-17.18
18.09	-14.46	3.34	-13.79	13.28	10.72	1.27	23.56	13.27	6.90	3.29	-11.73	-1.16	5.23	-2.67
-49.80	-17.28	-59.70	51.22	32.51	8.72	-48.52	-28.41	-44.42	-34.56	7.42	-6.93	7.09	-22.97	1.40
-9.41	-31.05	-1.28	8.65	9.34	-13.93	-9.02	7.64	18.39	0.81	24.06	-16.46	-10.58	-4.43	1.40
-11.12	4.39	-19.24	-3.78	-0.76	6.77	-12.76	-11.59	7.20	-0.09	20.37	3.63	3.30	-9.13	7.66
6.66	-42.19	7.88	25.04	-7.20	11.09	-8.13	-10.60	4.32	5.10	-21.87	4.98	5.82	-10.71	-7.07
29.46	23.26	14.61	-20.14	11.27	0.09	1.56	-3.45	-11.73	8.59	-35.20	1.87	-4.65	-6.77	5.48
-21.17	3.55	13.41	-2.04	37.53	10.55	-9.99	23.88	20.51	4.72	10.04	-5.29	-11.13	4.97	6.91
6.14	-7.27	10.33	-29.43	-2.03	-10.69	-0.67	-3.92	-19.22	-17.56	4.53	-13.58	-26.07	-1.45	-11.47
-9.63	15.61	4.19	10.36	13.87	-2.71	29.41	-10.78	10.10	-3.99	-5.65	3.46	-18.47	25.38	-15.09
-12.55	-6.82	-14.77	-13.70	-10.97	-14.95	-5.67	-26.38	2.76	8.51	-5.74	7.14	0.14	11.78	1.12
-13.39	-5.06	-26.56	-5.31	7.70	33.82	-22.72	-0.15	9.14	18.13	22.27	-17.42	5.77	-7.19	-2.80
-20.75	2.12	-21.31	20.30	-15.57	-9.92	-13.22	-7.64	23.18	8.69	9.08	14.96	0.31	8.01	20.62
-14.43	-28.60	7.66	-20.20	38.51	-28.03	14.30	14.05	5.34	13.92	-5.58	6.27	-16.87	21.27	-0.95
-9.21	8.30	16.45	-13.26	4.83	15.61	17.32	-1.61	-4.01	3.83	11.65	17.95	22.63	-6.07	18.72
-18.03	4.48	-0.34	-0.63	-10.42	-18.94	5.99	-20.36	-5.21	-9.73	-6.08	-2.33	-5.85	6.38	1.35
15.09	18.35	-13.50	3.30	-17.40	3.61	-6.53	-27.90	8.75	-0.64	8.38	8.74	3.08	5.15	2.65
-8.88	-16.14	-0.86	-7.06	-10.35	4.35	15.48	-6.66	13.32	-18.36	-6.13	-5.66	-8.42	-2.99	1.80
-8.88	-16.14	-0.86	-7.06	-10.35	4.35	15.48	-6.66	13.32	-18.36	-6.13	-5.66	-8.42	-2.99	1.80
27.25	0.98	25.46	11.57	17.53	-10.07	-12.56	-2.01	-7.87	-4.85	-25.80	4.58	3.28	12.66	-0.20
-22.16	-12.20	-19.52	-10.47	12.47	-3.77	-3.88	4.79	-30.39	-25.65	-1.55	14.10	-7.32	-3.24	2.43
-6.62	16.44	12.59	7.91	-7.41	-29.52	5.47	4.29	-2.01	6.66	9.68	-11.46	-0.53	-3.90	2.75
-27.67	13.15	-22.34	-2.89	8.83	10.48	-11.59	15.80	-17.69	-11.46	2.73	0.44	-3.91	-7.80	2.63
15.57	17.13	-23.82	2.67	-19.88	16.80	-25.66	-13.80	-6.54	22.65	-5.52	-6.11	19.57	7.85	7.74
-10.44	24.42	11.98	11.52	-19.22	-7.46	1.98	-14.94	-18.55	10.45	-10.94	12.71	-3.16	-4.02	3.29
-11.58	32.53	-40.66	20.19	-18.12	10.84	20.76	5.11	-5.56	-6.25	28.23	3.06	2.73	17.19	11.38

Table 12. DH parameters of chosen subjects mapped by PCA transformation, Part 5

-8.91	13.90	13.61	31.36	-13.98	-10.53	-6.19	3.40	5.02	-0.81	-6.92	-13.38	4.65	1.45	-1.12
17.52	8.41	9.36	-16.61	-9.04	-22.75	7.80	4.98	3.38	3.39	-2.99	4.78	-4.04	-0.80	-5.47
-9.47	-22.52	-3.32	-6.42	5.77	6.35	0.20	-10.14	-0.34	8.84	3.56	-8.19	-7.99	-1.74	-1.35
4.01	-20.26	16.49	7.24	1.67	12.10	-10.04	16.11	-15.00	0.35	5.57	-2.20	-2.24	-2.30	0.83
-8.04	-12.01	-1.11	-14.01	-7.03	10.65	-1.14	-4.39	-0.89	3.17	1.32	0.04	2.04	1.42	2.66
10.43	0.68	-15.40	-16.08	4.23	10.49	-6.90	0.19	2.37	20.02	-4.13	-1.40	0.75	-2.16	7.21
-17.04	13.09	13.31	-5.29	7.10	-11.22	-5.66	-3.87	7.49	-7.05	3.43	2.15	-4.77	4.03	-4.97
-8.12	7.39	-21.69	5.78	3.38	16.30	-8.24	-4.54	6.17	-0.96	7.09	-4.26	1.79	1.36	-3.79
-3.76	-29.02	-16.80	13.42	-10.06	-10.30	17.44	-8.38	6.84	0.88	-6.31	8.24	0.41	-1.90	12.86
0.21	15.03	-1.46	0.46	1.32	-6.59	-2.17	-1.74	-1.63	1.12	-7.98	-3.46	0.49	5.80	-1.14
9.07	10.61	-12.97	13.13	-8.51	-2.67	-6.18	5.79	4.69	-6.81	-5.31	-9.94	8.68	5.06	6.37
2.65	0.12	10.66	6.39	-5.00	-2.07	-12.81	0.06	0.03	-7.73	8.27	-1.18	0.92	2.15	0.04
4.82	3.16	-2.04	-4.85	7.84	0.94	-11.99	-4.51	-1.79	7.55	5.29	-8.59	-1.81	3.56	-0.61
-8.17	-2.34	8.44	-2.80	-9.20	20.49	6.84	3.93	22.04	-7.17	6.27	1.60	6.77	4.85	2.59
-11.11	-7.86	-1.83	-1.62	9.37	-1.03	10.73	8.22	6.38	0.01	-4.14	-4.07	1.73	0.37	-0.50
-14.06	-20.34	5.44	4.97	2.66	-1.51	3.47	4.92	-5.98	-6.26	-2.28	3.77	-5.01	-4.95	-4.29
-4.78	-18.13	-14.30	-17.12	-10.95	9.47	8.47	5.03	-8.43	-4.55	-4.99	13.12	-9.76	-6.93	-6.13
0.44	-9.16	5.72	7.38	-5.56	-2.30	13.69	-1.17	-7.82	5.18	-7.46	0.39	6.79	3.96	-4.63
-2.00	3.08	3.37	1.65	-11.68	1.50	-11.57	-0.09	0.53	3.36	8.25	-0.08	4.38	-0.97	2.54
2.94	1.35	8.19	7.28	-12.42	5.13	2.69	9.24	-8.88	0.23	-3.92	-0.58	3.06	0.41	7.93
-2.08	-4.94	-13.18	8.88	9.65	0.58	4.77	9.79	-13.71	-14.47	1.82	-2.36	-0.28	-6.21	-4.75
-8.12	-6.03	2.30	-1.33	11.10	9.22	1.95	3.82	14.87	-13.61	5.54	4.85	17.27	1.82	-3.10
-9.22	-12.01	-1.25	6.51	14.74	6.84	10.50	6.73	-0.17	7.68	6.80	7.49	-2.99	-3.07	-0.06
-26.93	7.66	-10.68	-4.72	-22.83	-4.14	-18.99	-4.98	4.06	-1.38	-11.94	-6.84	-5.83	3.04	-1.78
5.30	-4.26	1.56	11.57	-9.38	-4.79	5.51	-2.75	-5.20	8.02	2.55	5.54	6.19	-2.82	-0.54
5.75	1.35	-6.75	6.69	8.28	3.72	8.04	-5.42	-1.67	9.73	1.70	-4.31	-1.87	2.87	3.45
-14.76	10.56	-5.93	1.35	16.26	9.02	24.64	-12.60	-12.23	1.78	-9.92	-1.39	-5.85	9.59	-10.88
1.71	3.30	-8.10	5.94	1.82	31.85	0.01	5.41	1.28	10.07	-0.51	-7.95	-0.44	-1.08	-1.25
7.22	10.73	12.82	-0.54	0.09	6.04	1.53	-3.62	-14.45	17.10	-13.86	6.37	-6.21	-6.92	12.95
5.14	0.72	-10.08	-1.47	4.20	-0.88	-4.53	8.83	9.44	-1.01	-0.77	-6.89	9.99	11.22	7.63
4.90	1.02	4.41	8.79	-7.28	10.88	-3.15	-1.92	-0.43	4.89	-2.81	-3.92	6.19	-5.35	4.91
0.26	-0.48	6.63	-3.39	-5.18	4.61	-6.67	-6.02	-2.94	-0.73	1.57	1.63	-2.80	0.09	-0.08
0.26	-0.48	6.63	-3.39	-5.18	4.61	-6.67	-6.02	-2.94	-0.73	1.57	1.63	-2.80	0.09	-0.08
6.42	3.14	15.30	10.82	6.62	3.07	7.22	7.94	4.33	-4.78	1.34	-1.77	0.19	1.00	-3.07
-22.90	3.89	-9.15	-6.07	3.26	-8.64	-8.21	-8.59	-2.55	-0.60	1.11	5.79	4.39	3.36	-3.15
-1.70	-0.41	-2.74	2.88	-2.58	-8.35	4.14	-2.88	5.41	3.75	-3.48	7.08	0.68	6.95	-3.81
-10.27	-0.96	2.93	-0.22	-17.76	-2.37	-7.79	-7.59	-12.79	-0.54	1.36	-0.45	0.84	-5.56	4.83
-3.95	-5.01	1.73	13.54	-9.20	2.45	6.85	-0.17	-5.65	3.56	1.37	3.63	0.37	-3.02	-3.17
-10.81	-0.86	5.20	17.72	0.12	4.12	9.53	-11.09	6.38	1.24	7.97	4.68	5.50	6.15	3.38
-7.02	15.04	-4.33	-3.95	7.60	0.93	6.50	7.74	-5.38	-10.06	-2.70	-1.50	-2.53	4.20	3.61

Table 13. DH parameters of chosen subjects mapped by PCA transformation, Part 6

-7.14	-5.22	6.61	-1.30	-2.56	-5.64	-3.54	1.24	-0.96	-3.95	4.83	-3.39	1.65	1.03	1.13
-5.93	-1.16	0.81	3.20	6.48	3.83	2.97	2.85	5.42	0.09	-0.98	-3.06	-1.48	-1.39	-0.90
6.62	-1.87	2.78	3.63	-0.84	1.26	-2.25	1.79	-5.54	-2.97	2.03	-0.11	1.96	-1.92	-0.16
-3.41	8.04	-1.69	0.51	-4.31	2.99	-0.97	-1.35	-0.02	-5.86	-5.45	1.58	-0.16	-0.58	0.61
-0.76	-0.99	-2.52	1.13	1.91	3.61	0.50	-2.18	0.77	-2.27	-0.33	-1.23	-0.94	-1.98	1.44
-2.11	-2.77	1.11	1.51	-2.41	0.88	1.77	2.40	2.06	5.98	-2.01	-3.80	-1.25	1.70	-3.45
0.79	3.56	6.66	-1.54	-2.72	8.73	-5.27	0.79	1.09	5.27	1.39	-0.35	0.48	-0.19	0.57
-3.31	0.06	4.78	-1.36	1.99	2.32	-2.02	0.39	-2.23	1.19	3.18	-2.13	-2.00	-3.33	-3.13
-0.67	-6.36	-6.61	-19.19	6.19	-6.92	-0.41	-2.24	-0.50	0.48	-6.99	-3.14	2.15	1.29	-1.06
0.33	3.70	-1.80	-0.85	-0.90	6.05	-2.53	-6.00	-2.91	3.50	-0.31	-1.18	-1.70	1.33	1.13
3.82	6.45	1.86	0.92	-4.01	6.25	2.79	-0.93	-0.38	0.74	2.88	0.51	0.92	-6.06	-1.98
-0.76	2.72	0.24	-4.77	-2.24	-1.48	-0.38	-2.80	3.21	-2.92	-1.16	1.47	-0.39	-0.09	1.18
2.46	0.89	-4.73	-4.48	1.79	-1.19	2.05	-0.78	3.78	-2.43	1.63	0.43	1.04	-2.47	1.47
3.73	-7.09	3.90	-3.72	6.90	3.70	-6.52	-3.75	-0.92	1.64	-1.42	2.37	-1.16	-0.89	-2.95
3.13	2.88	-1.24	-0.41	-3.87	-2.05	-4.31	-2.30	0.55	-1.44	1.12	-3.43	-1.71	1.27	-3.44
-2.89	1.29	0.10	-4.74	1.32	1.96	2.51	-1.24	3.47	0.00	-0.73	1.80	-2.11	0.24	-0.70
5.26	-4.23	-6.86	-3.46	0.97	-3.34	-3.90	-0.89	-1.31	2.30	3.19	1.91	0.32	0.05	-1.19
-7.28	-6.47	-4.68	4.30	-1.14	-5.09	2.84	4.47	-2.85	-4.89	6.10	-1.83	-1.75	0.02	1.11
5.98	0.62	-2.31	1.43	1.08	0.96	1.26	0.68	-0.14	-0.83	-0.07	1.62	-1.25	0.13	-1.16
5.10	-3.00	-1.75	-1.15	4.80	0.36	2.52	2.39	-2.55	-0.20	-3.55	-0.28	0.35	0.58	0.07
2.60	6.97	1.89	-3.21	-1.16	-2.08	-0.00	-5.46	3.93	1.22	4.40	-2.90	4.31	2.96	0.18
4.48	-2.65	4.84	5.03	-2.50	2.14	2.21	-1.21	-0.41	-0.54	0.04	-0.46	-2.61	4.00	0.30
6.33	9.13	2.84	5.85	0.88	-6.59	2.72	0.97	0.84	1.28	-2.38	3.98	2.50	-0.35	0.34
-8.78	4.77	2.83	-7.91	-3.17	2.00	3.07	3.59	-4.14	1.14	0.34	0.04	1.35	2.79	-0.57
-6.38	-3.12	4.22	0.54	1.44	4.15	-1.99	0.14	0.00	1.86	1.01	0.72	-0.94	-0.66	0.67
0.61	5.00	0.48	4.89	-0.46	1.85	-3.74	-0.08	1.34	0.25	-0.51	2.04	-1.51	-2.43	1.34
-1.92	-6.26	9.34	-2.98	-0.32	4.83	5.92	-8.31	11.43	2.19	-3.94	0.68	-0.52	-3.09	2.18
-10.34	-5.28	-6.42	1.99	1.97	-1.11	-1.31	2.63	-0.67	2.57	-0.27	1.52	1.03	-3.10	3.65
-4.12	5.46	-2.50	2.87	0.99	-3.89	3.29	2.54	-3.96	-2.69	4.68	3.74	-2.46	-2.10	1.97
-6.52	5.12	0.17	-5.18	-2.97	3.20	-0.72	0.51	3.20	-2.58	4.27	-2.29	-0.99	2.76	-2.88
-1.35	-3.70	2.02	2.46	0.74	-0.22	-0.45	1.20	3.57	0.99	-1.51	2.16	3.19	-0.68	-0.81
-0.59	0.79	5.60	0.75	0.40	-3.31	3.02	2.17	3.58	0.47	1.36	-3.29	-1.56	-0.47	2.25
-0.59	0.79	5.60	0.75	0.40	-3.31	3.02	2.17	3.58	0.47	1.36	-3.29	-1.56	-0.47	2.25
-2.87	-0.79	-4.98	1.17	-2.53	-0.82	2.65	3.36	0.14	0.54	-2.35	-0.10	0.89	-2.49	1.58
4.66	0.80	-1.09	-0.40	-2.18	-0.12	-2.38	-1.63	-1.94	-1.66	-0.92	2.27	1.33	-0.44	-0.64
0.10	3.67	-3.42	9.43	6.93	-0.26	-1.38	-5.61	-6.52	-4.99	-2.00	-0.91	0.20	-2.46	1.62
-0.51	0.59	2.05	-0.66	1.56	2.60	1.26	0.50	-3.87	-0.09	2.48	2.65	1.04	0.53	-2.78
-3.81	2.04	-1.11	3.25	5.12	5.17	2.86	1.16	-2.47	-1.48	2.96	0.93	2.91	2.51	-2.58
-3.95	3.73	2.11	-0.28	-0.44	-2.61	-2.09	-0.63	-1.37	2.52	2.12	-0.10	-0.23	1.83	-0.75
1.29	9.68	-3.24	3.75	-0.10	-3.82	3.30	-1.45	-2.67	-1.12	-4.57	-3.80	-0.29	1.95	-0.17

Table 14. DH parameters of chosen subjects mapped by PCA transformation, Part 7

2.75	-1.63	-0.79	-2.00	-1.49	0.00	-0.09	0.02	0.09	0.08	0.06	-0.00	-0.03	0.00
-0.57	1.23	1.42	1.36	-0.19	0.01	-0.08	-0.03	-0.03	-0.05	-0.02	0.01	0.05	-0.01
0.70	-0.31	-0.76	1.75	-0.04	0.03	0.07	-0.08	0.04	0.00	-0.07	-0.01	-0.01	-0.00
-0.06	-1.89	0.11	2.07	0.38	0.05	-0.01	0.02	0.02	0.03	-0.09	0.02	0.02	-0.03
1.26	-2.32	0.65	-0.56	-1.69	0.00	-0.05	-0.05	0.01	-0.03	0.04	0.02	-0.03	-0.01
2.50	-1.40	0.09	-0.68	1.17	0.02	0.05	0.02	0.05	-0.01	-0.01	0.00	0.02	-0.01
-0.53	-0.22	4.91	-0.96	-1.98	-0.18	0.08	-0.02	-0.02	-0.00	0.05	0.01	0.00	0.02
1.76	1.97	-1.56	0.98	0.09	0.00	-0.02	0.02	-0.03	-0.01	0.01	-0.02	-0.01	-0.00
-0.29	1.08	0.59	0.50	0.99	-0.02	0.02	-0.02	-0.03	-0.01	-0.01	-0.01	-0.01	0.01
-2.33	1.84	-1.83	0.54	0.46	0.03	-0.03	-0.11	0.00	-0.02	-0.02	0.01	-0.02	0.01
-0.16	2.39	0.83	-0.11	-0.93	0.05	-0.01	0.03	-0.04	-0.01	0.01	0.03	0.01	0.01
-1.64	0.55	-0.17	-2.10	-1.49	-0.08	-0.05	-0.04	-0.05	0.00	-0.02	0.01	0.01	0.03
1.25	0.55	-1.95	1.35	0.28	0.02	0.03	-0.01	0.02	0.02	0.02	0.02	-0.04	0.03
-0.06	2.18	-1.30	0.10	0.27	-0.08	0.03	-0.00	0.00	0.01	0.02	-0.01	0.01	-0.00
-3.02	-1.46	1.34	0.36	-2.23	-0.01	0.07	0.03	0.04	-0.02	-0.04	0.03	0.03	-0.01
-1.16	-2.16	-0.07	0.28	0.29	0.02	-0.09	-0.01	-0.04	-0.02	0.00	-0.00	0.05	0.00
-2.00	0.58	-2.18	-0.06	0.58	-0.01	0.02	-0.02	0.00	0.05	-0.01	0.00	-0.00	0.01
2.26	1.24	-1.49	1.03	-2.27	-0.04	-0.05	-0.07	-0.07	0.09	0.01	0.02	0.02	-0.01
0.73	1.47	0.75	1.32	0.43	-0.10	0.04	-0.05	-0.01	0.05	0.02	-0.00	-0.05	-0.04
3.62	0.34	-0.33	0.25	-1.14	-0.03	-0.05	0.01	-0.00	0.03	-0.05	0.01	0.01	-0.01
0.21	0.36	0.18	-2.53	-1.32	0.05	0.04	-0.01	0.04	0.04	0.01	-0.03	0.03	-0.02
-0.46	-0.08	-3.15	0.41	-0.82	0.05	0.02	0.04	0.05	-0.02	-0.02	-0.01	0.03	-0.02
1.34	1.47	0.88	-0.12	0.16	0.05	-0.03	0.06	0.04	0.05	0.03	-0.03	0.00	-0.01
0.12	0.23	0.74	0.61	1.17	0.00	-0.00	0.07	-0.00	0.00	-0.03	-0.00	-0.01	-0.01
-3.47	0.16	1.45	1.12	-0.57	0.12	-0.06	-0.00	0.07	-0.02	0.03	-0.05	0.01	0.00
0.86	0.69	1.07	0.07	0.88	0.01	-0.01	0.03	-0.03	0.03	-0.03	0.03	-0.01	-0.00
-0.02	-1.07	-1.12	-0.71	-0.36	-0.07	-0.06	-0.03	0.03	0.01	-0.03	-0.04	-0.01	-0.01
-0.77	0.12	-0.68	-1.61	0.23	0.04	0.06	0.01	0.00	0.05	-0.01	0.01	0.01	0.03
0.06	2.76	-0.64	-1.59	0.61	-0.01	0.00	-0.06	0.05	-0.07	0.04	-0.03	0.00	-0.00
0.09	1.12	-0.68	-0.33	1.10	-0.05	0.05	-0.07	-0.03	-0.02	0.02	0.00	0.00	-0.02
0.63	0.43	2.07	-0.32	-0.59	-0.07	0.08	0.00	0.02	0.04	-0.05	0.04	0.01	0.02
-1.32	1.92	-0.60	-0.46	1.36	0.01	0.02	0.05	-0.00	-0.02	-0.00	0.03	0.03	0.00
-1.32	1.92	-0.60	-0.46	1.36	0.01	0.02	0.05	-0.00	-0.02	-0.00	0.03	0.03	0.00
-3.02	2.42	-1.33	-1.27	-2.27	0.06	0.08	-0.09	-0.06	0.01	-0.03	-0.02	-0.01	-0.04
0.16	0.01	-1.07	-0.40	0.12	0.02	-0.05	-0.01	0.01	0.01	0.03	-0.01	-0.01	0.00
-1.73	0.63	1.94	-1.87	1.87	-0.11	0.02	0.18	-0.05	0.04	-0.00	0.01	0.05	0.01
-0.25	-0.85	-1.74	0.31	0.74	-0.01	-0.01	-0.02	-0.04	0.01	0.03	-0.01	0.04	0.00
-1.71	-2.22	0.87	1.23	0.44	0.01	-0.05	0.01	0.01	-0.03	0.01	0.02	-0.02	0.02
2.05	-1.30	-0.72	0.72	0.22	0.00	-0.02	-0.01	0.02	0.03	-0.02	0.00	0.00	-0.01
0.96	-0.74	-0.18	-0.51	-0.67	-0.06	-0.01	-0.03	-0.01	0.02	-0.03	-0.03	-0.00	-0.02

Appendix F: Display of single model optimization results

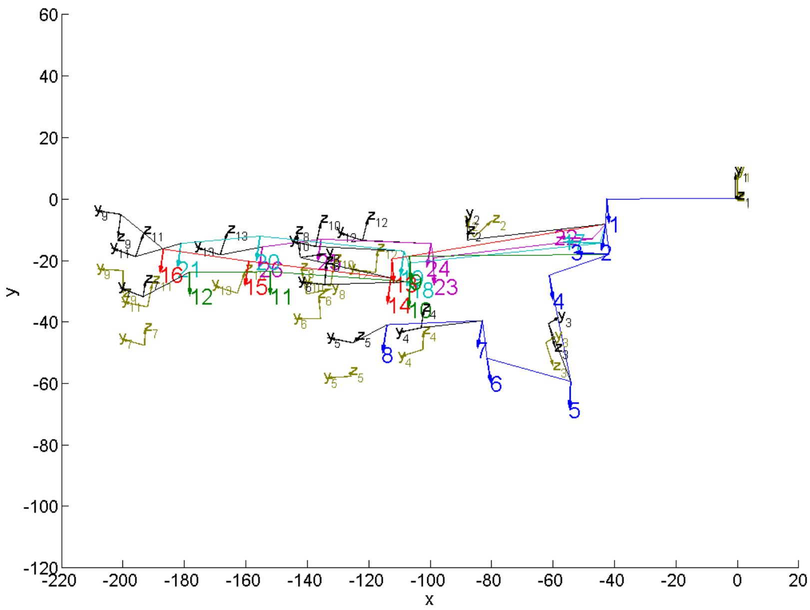

Figure 15: An example of single model optimization result.

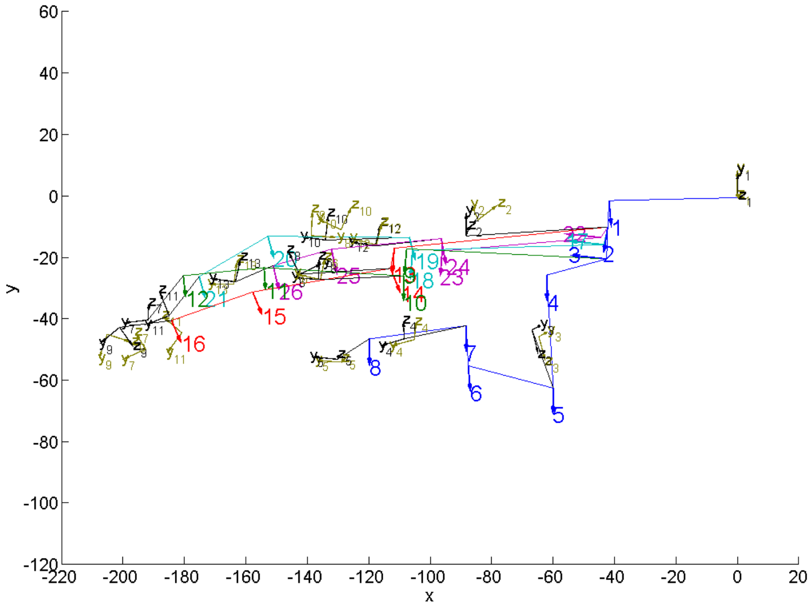

Figure 16: An example of single model optimization result.

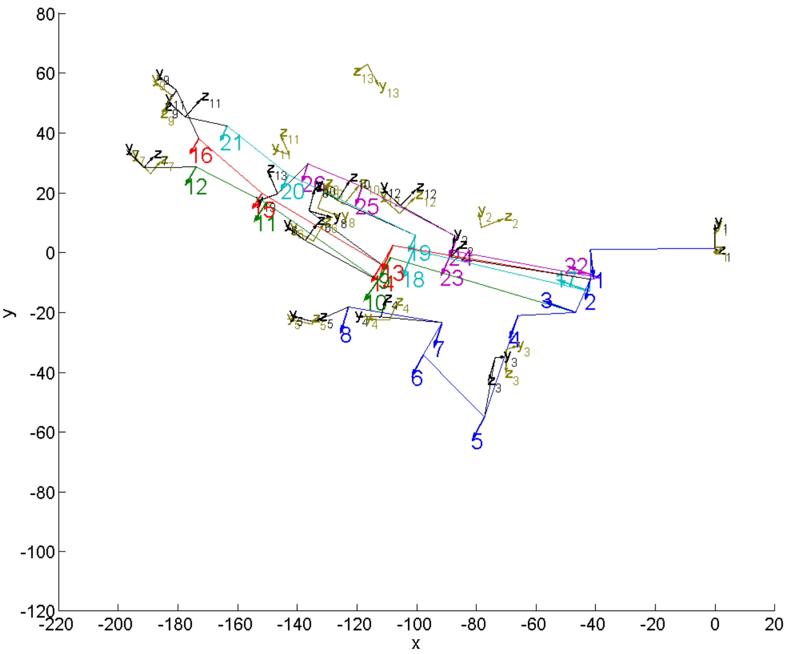

Figure 17: An example of single model optimization result.

APPENDIX G: MATLAB CODE SAMPLES

This appendix contains Matlab code samples that illustrate cost function computation.

```
function [cost] = cost_fcn(delta_x, x0, scale_x, optimise_DHHS, DHHS0, nearly_parallel0, chains_axes, axes_parents,...
    segments_axes, segments_axes_single, optimise_T_ref, euler_order, euler_order_inner, jointangles0, synergy_matrix, ...
    optimise_synergies, size_a, size_b, size_c, size_d, size_syn, size_eul, T_meas, T_meas_pos, T_ref0, T_ref0_pos, ...
    weight_r, weight_t, proband)
%% COST_FCN_
%% Computes the global cost function value. This value is optimized to
%% get a hand kinematics model


    N = size(T_meas,4);

    % extract parameters from the parameter vector
    x = x0(:) + delta_x(:).*scale_x;
    %% DH parameters
    DHHS = DHHS0;
    DHHS(optimise_DHHS) = x(1:sum(optimise_DHHS(:)));
    [axpos,axorient] = DHHS_to_CartAxes(DHHS,nearly_parallel0,axes_parents);
    % Reference posture
    T_ref = T_ref0;
    optimise_T_ref_numbers = find(optimise_T_ref);
    for i_s = 1:numel(optimise_T_ref_numbers) %#ok<FXUP>
        s = optimise_T_ref_numbers(i_s);
        if euler_order(s)==1
            T_ref(:,:,s) = [
                euler2matXYZ(x(sum(optimise_DHHS(:))+(i_s-1)*6+(1:3))),...
                x(sum(optimise_DHHS(:))+(i_s-1)*6+(4:6));
                0 0 0 1];
        else
            T_ref(:,:,s) = [
                euler2matXZY(x(sum(optimise_DHHS(:))+(i_s-1)*6+(1:3))),...
                x(sum(optimise_DHHS(:))+(i_s-1)*6+(4:6));
                0 0 0 1];
        end
    end


    % Joint angles
    synergies_x_t = x(size_a+size_b+1:size_a+size_b+size_c);
    % Global pose
    eulerpose_x_t = x(size_a+size_b+size_c+1:size_a+size_b+size_c+size_d);
    dorsal_shift = x(numel(x))
    % Compute cost values for all postures
    norm_cost_posture = nan(N,1);
    for n = 1:N %#ok<FXUP>
        syn_ind1 = (n-1)*size_syn+1;
        syn_ind2 = n*size_syn;
        eul_ind1 = (n-1)*size_eul+1;
        eul_ind2 = n*size_eul;
```

```
            [norm_cost_posture(n)] = cost_fcn_with_pose(synergies_x_t(syn_ind1:syn_ind2), eulerpose_x_t(eul_ind1: eul_ind2),n,...
                axpos, axorient, T_ref, T_ref0_pos, T_meas, T_meas_pos, weight_r, weight_t, jointangles0, synergy_matrix, ...
                optimise_synergies, chains_axes, segments_axes, segments_axes_single, euler_order_inner, dorsal_shift);

        end
        % calculate cost
        cost = nanmean(norm_cost_posture);
        % save intermediate values
        if (cost<10)
            save(['temp_results_', proband, '.mat'],'delta_x','norm_cost_posture');
        end


    end
```

```
function [cost] = cost_fcn_with_pose(synergies_in, eulerpose_in, n_in, axposition, axorientation, T_ref_in, T_ref0_pos, T_meas,...
      T_meas_pos, weight_r, weight_t, jointangles0, synergy_matrix, optimise_synergies, chains_axes, segments_axes, ...
    segments_axes_single, euler_order_inner, dorsal_shift)
%% COST_FCN_WITH_POSE
%% Computes the cost function value for each time sample. This value further
%% participates in the global cost function


     S = size(T_meas,3);
    S_s = size(T_meas_pos,2);

        %% Get global pose and joint angles
        synergies = synergy_matrix\jointangles0(:,n_in);
        synergies(optimise_synergies) = synergies_in;
        eulerpose = eulerpose_in;
        jointangles_curr_n = synergy_matrix * synergies;

        if (euler_order_inner(n_in)==1)
            pose_curr_n = [
                euler2matXYZ(eulerpose(1:3)) eulerpose(4:6)
                0 0 0                            1];
        else
            pose_curr_n = [
                euler2matXZY(eulerpose(1:3)) eulerpose(4:6)
                0 0 0                            1];
        end

        % Forward kinematics
        % Compute modelled posture based on the reference posture and
        % current joint angle values
        [T_mod, T_mod_pos] = Fkine_Branching_GloPose_CartRotAxes(chains_axes,segments_axes, segments_axes_single,T_ref_in, T_ref0_pos, ...
            axposition,axorientation,jointangles_curr_n,pose_curr_n, dorsal_shift);
        % Compute cost as difference between the measured and the modelled
        % posture
        T_meas_inv = nan(size(T_meas(:,:,:,n_in)));
        for k = 1:S
            T_meas_inv(:,:,k) = Tinv(T_meas(:,:,k,n_in));
        end
        T_diff = MAMAProduct(T_meas_inv,T_mod);
        T_diff_pos = zeros(3,S_s);

        for k = 1:S_s
            T_diff_pos(:,k) = (T_meas_pos(:,k,n_in)-T_mod_pos(:,k));
        end
        angles_diff = MA2ang(T_diff(1:3,1:3,:));
        distances_diff = M2norms(squeeze(T_diff(1:3,4,:)));
        distances_diff_pos = M2norms(T_diff_pos);
```

```
    cost = nanmean([angles_diff*weight_r;distances_diff*weight_t;distances_diff_pos*weight_t]);

end
```