The Study of Complex Manipulation via Kinematic Hand Synergies: The Effects of Data Pre-Processing

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ABSTRACT

The study of kinematic hand synergies through matrix decomposition techniques, such as singular value decomposition, supports the theory that humans might control a subspace of predefined motions during manipulation tasks. These subspaces are often referred to as synergies. These **synergies have often been used as the basis of both rehabilitative and prosthetic hand devices.** However, **different data pre-processing methods lead to quantitatively different conclusions about these synergies**.

In this work, we shed light on the role of data pre-processing on the study of hand synergies by analyzing both numerical simulation and real kinematic data from a complex manipulation task, i.e., piano playing. The results obtained suggest that **centering the data, by removing the mean, appears to be the most appropriate pre-processing technique for studying kinematic hand synergies.**

METHODS

Theoretical Background

1. Given Data Matrix → $X \in R^{(observations \times time) \times joints}$

$$X = \begin{bmatrix} observation1_{joint\ 1}@t=0 & \cdots & observation1_{joint\ n}@t=0 \\ \vdots & \ddots & \vdots \\ observation1_{feat1}@t_{final} & \cdots & observation1_{joint\ n}@t=t_{final} \\ & \vdots & \\ observation4_{joint\ 1}@t=0 & \cdots & observation4_{joint\ n}@t=0 \\ \vdots & \ddots & \vdots \\ observation4_{feat1}@t_{final} & \cdots & observation4_{joint\ n}@t=t_{final} \end{bmatrix}$$

2. Singular Value Decomposition on X → $X = U \cdot S \cdot V^T$ where,
   - **Synergy Matrix →** $V \in R^{joints \times joints}$
   - **Diagonal Variance Matrix →** $S \in R^{(observations \times time) \times joints}$
   - Temporal Evolution → $U \in R^{(observations \times time) \times (observations \times time)}$

Example Data Pre-Processing Methods

Raw Data: $X = X$

Mean Removed Data: $X_{rm} = X - mean(X)$

Z-scored Data: $X_{zs} = \frac{X - mean(X)}{std(X)}$

Range 0 to 1 Data: $X_{r01} = \frac{X - min(X)}{\max(X - min(X))}$

Numerical Validation

Simulated 2-DOF system where:

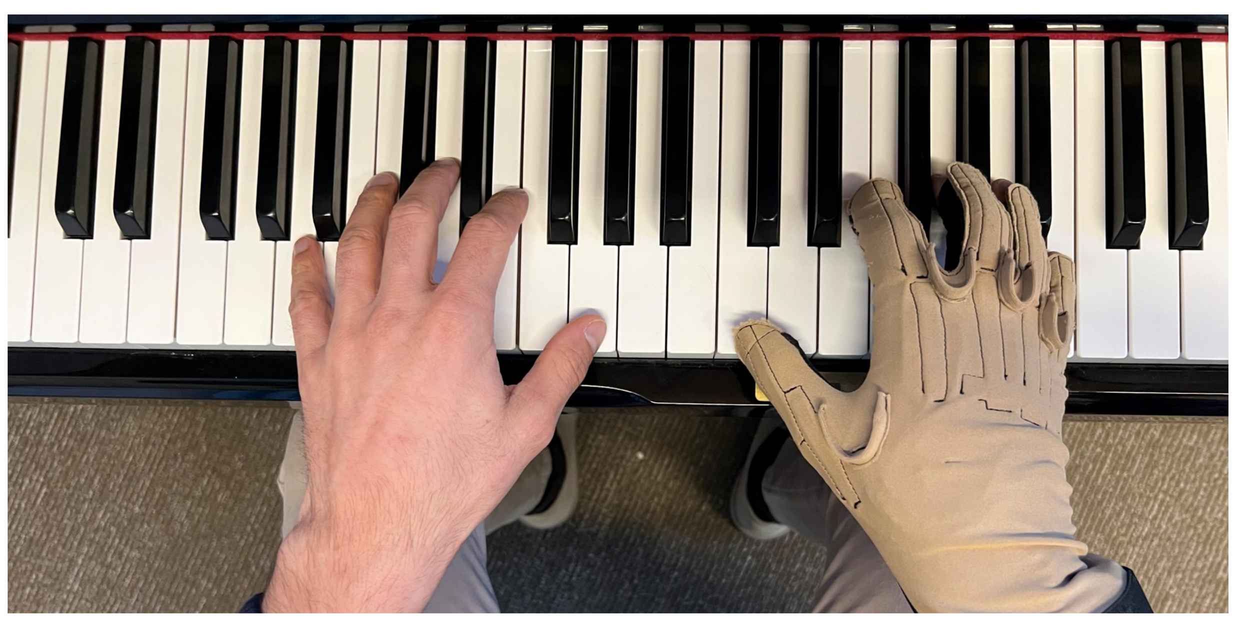
$$X = [x_1, x_2] \text{ and}$$

$$x_2(i) = \mathbf{0.50}x_1(i) + 3 + noise \qquad i = 1, \ldots, 101$$

Note the embedded synergy $x_2 = \mathbf{0.50}x_1$.

Piano Playing

Twenty-three relative hand joint angles of one subject playing the piano were measured using a CyberGlove. The subject played 7 different pieces.



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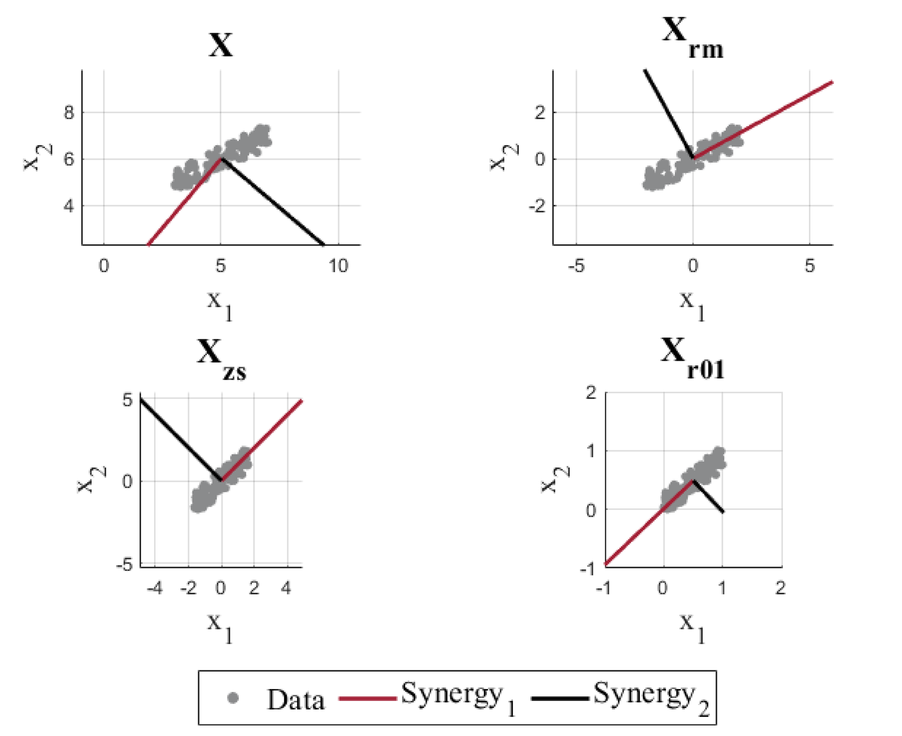
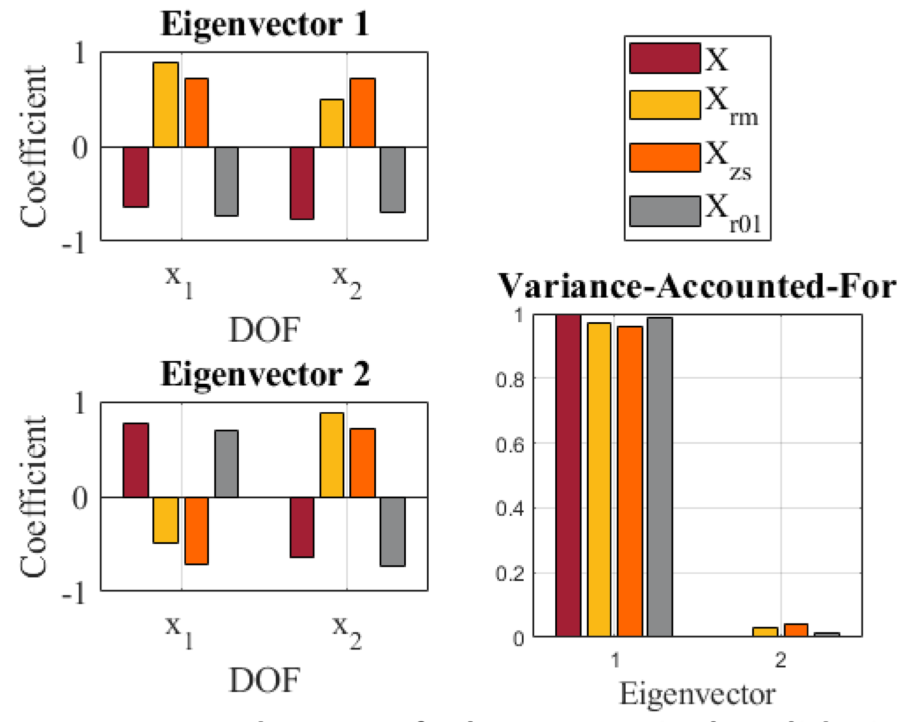
RESULTS

Numerical Validation



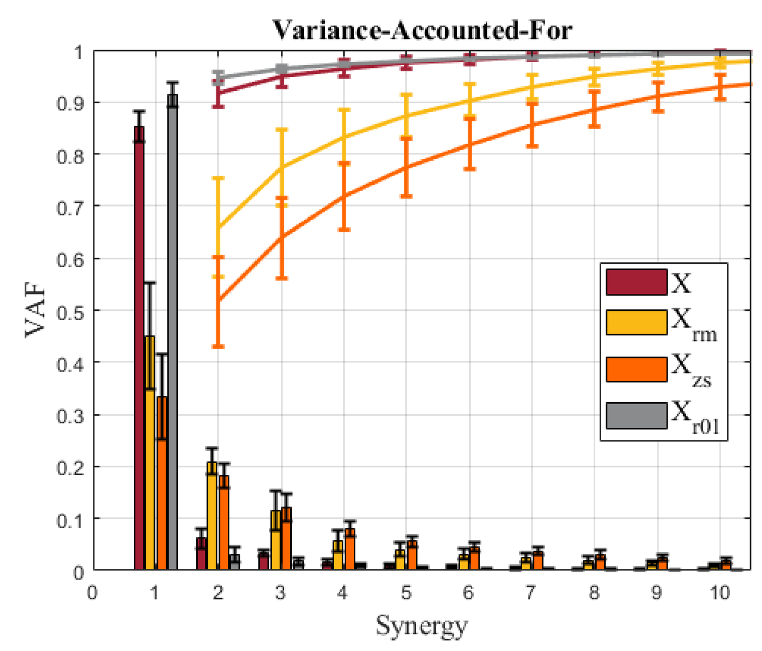
Numerical validation data of the various pre-processing types and the 1st and 2nd eigenvectors (i.e., synergies). (a), (b), (c) and (d) denote the raw, mean-removed, z-scored, and range 0 to 1 data, respectively. Note, the mean values of the raw data are 6.022 and 5.013; their ratio is 1.201. Additionally, the mean values of the range 0-1 data are 0.486 and 0.503; their ratio is 0.967.



Eigenvectors and VAF of the numerical validation data. Different colors denote different pre-processing types. The observed ratio of the coefficients of the first eigenvector was 1.177, 0.550, 1.000, and 0.952 for the raw, mean-removed, z-scored, and range 0 to 1 data, respectively. The VAF of the first eigenvector was 0.995, 0.968, 0.957, and 0.989 in the raw, mean removed, z-score, and range 0-1 data, respectively.

- **Only the mean-removed data estimated an approximately correct slope (0.550).**
- **When the data was not centered, the first synergy was directed towards the mean of the data.**
- **When the data was not pre-processed, the second synergy was considered to negligibly contribute to the variation of the data.**

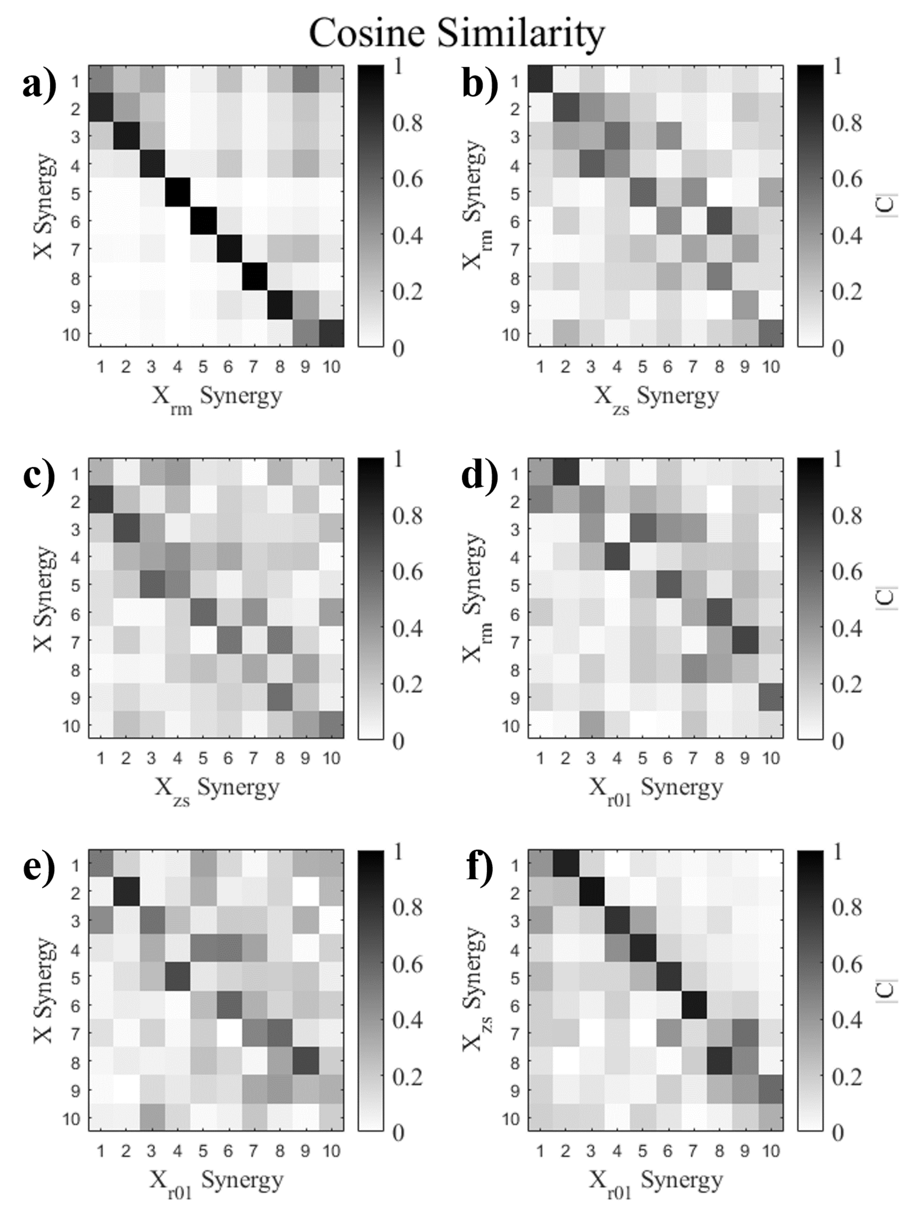
Piano Playing



VAF of the first 10 synergies in the piano experiment averaged across piece. Different colors denote different pre-processing types. Lines show the cumulative sum of the VAF. Error bars are ±1SD.

	X	X_{rm}	X_{zs}	X_{r01}
Avg	2.29	6.14	9.00	1.14
SD	0.49	0.90	1.63	0.38

Number of significant synergies, defined as the number of synergies required to achieve at least 90% VAF and where inclusion of another subsequent synergy did not add an additional 5% VAF, in the piano playing study based on data pre-processing.



The matrices of cosine similarities between synergies of different pre-processing types are presented for 1 piece. A black value denotes a cosine similarity of 1 and a white value denotes a cosine similarity of 0. A perfect similarity is denoted by a matrix with 1's (black) on the diagonal and 0's (white) elsewhere.

- **There is a significant effect of pre-processing type on the number of significant synergies.**
- **High similarity is seen on the subdiagonal of the cosine similarity matrix when the synergies from the raw data and the mean removed data are compared (a). This is similarly observed on the superdiagonal upon comparing the synergies from the z-scored and the range 0 to 1 data (f).**
- **Together, these results suggest that not centering the data will lead to a dominant first synergy with subsequent synergies that are consistent with the synergies of the centered data.**

CONCLUSION

- **Not centering** the data leads to a **dominant first-synergy** that is not representative of the principal directions of motion.
  - This would **lead a researcher to ignore** the also **important lower-order synergies**.
- **Changing the variance** of the data will lead to a synergy that demonstrates that certain DOFs do, indeed, co-vary but it will not quantify how much.
- **Thus, we recommend the pre-processing step of removing the mean.**
- The understanding of how pre-processing affects synergy decomposition presented here can **better inform** the **selection of the quantity and kinematic coupling of synergies** that **assistive** and **prosthetic hand devices should implement**.
- Here we demonstrate a rich manipulation task, piano playing. Future work will aim to expand the study of shoulder, arm, and hand **kinematics during piano playing** to uncover the **role of synergy decomposition** in this **complex manipulation** task.