Analysis of Human Pivoting Operations Using Hidden Markov Models

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Abstract

In this paper, human pivoting operations, a typical graspless manipulation, are studied. We model data of finger motions in pivoting operations using Hidden Markov Models (HMM). The "optimal" HMM with an appropriate number of states is determined based on the MDL (Minimum Description Length) criterion. The obtained HMMs are analyzed by metric MDS (Multidimensional Scaling) to reveal individual characteristics in the operations. This dissimilarity analysis can be used for the validation of models of tacit skills of human manipulation.

Introduction

Human manual dexterity

- Mechanism behind it is not yet well-understood
- Models of human skill must be investigated
- Validity of a model should be evaluated:

how well does it model the mechanism behind human dexterity?

HMM-based skill modeling

([Hannaford 91] [Yang 94] [Nechyba 98] [Itabashi 98] …)

- A powerful tool for modeling human manipulation, which has considerable variations
- Dissimilarity analysis is possible ([Nechyba 98] [Itabashi 98])

HMM topology

- model accuracy (complex topology) v.s. model simplicity (simple topology)
- empirically determined in most robotics literatures

Objective

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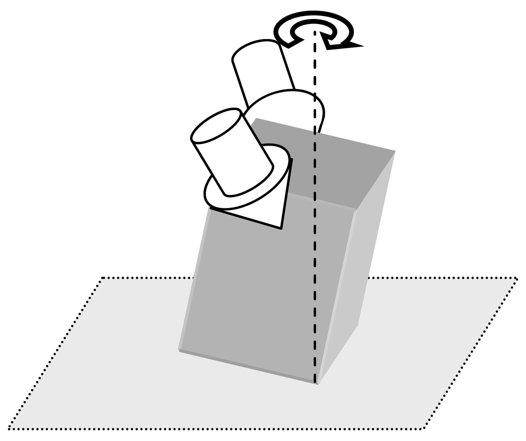
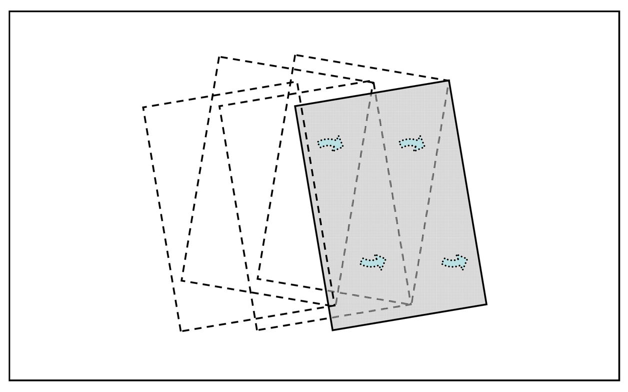
to present a method to validate models of human skill

Approach

- MDL-based hidden Markov modeling: objective determination of HMM topology
- Dissimilarity analysis based on MDS: can be used to validate models of human skill

Example task: pivoting



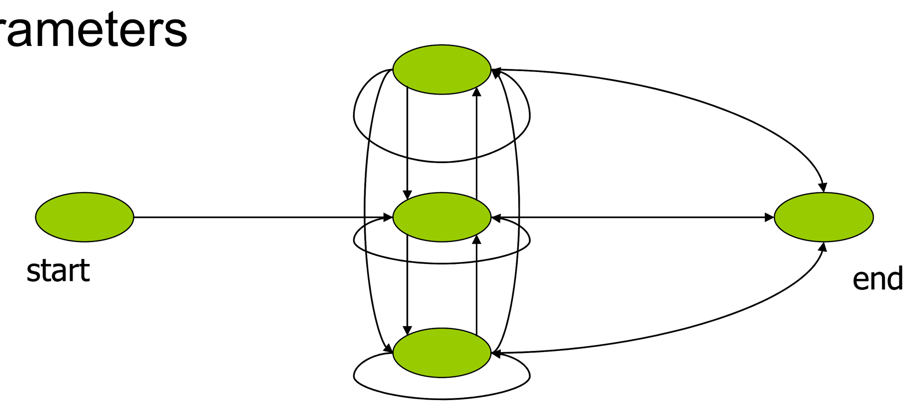


- typical graspless manipulation
- suitable to manipulate heavy objects
- dexterous manipulation as an outcome of appropriate interaction between human and environment

MDL Application to HMM

Hidden Markov Modeling

- HMM (Hidden Markov Models)
  - Markov process with hidden parameters
  - The state is not directly visible
- Continuous HMM
  - Output pdf: Gaussian mixture
  - Ergodic-like topology
  - Number of states: unknown



HMM Parameters

$$\boldsymbol{\lambda} = (\boldsymbol{A}, \boldsymbol{w}, \boldsymbol{\mu}, \boldsymbol{\Sigma}, \boldsymbol{\pi})$$

- $\boldsymbol{A}$: state transition matrix
- $\boldsymbol{w}$: weights, $\boldsymbol{\mu}$: means, $\boldsymbol{\Sigma}$: covariances (for Gaussian mixture pdf)
- $\boldsymbol{\pi}$: initial state probabilities

- Estimated using Baum-Welch algorithm

Minimum Description Length (MDL) Criterion

An objective measure for accuracy/complexity balance

• A model that minimizes MDL criterion is considered as "best"

$$-\log p^T_{\hat{\boldsymbol{\theta}}(i)}(\boldsymbol{O}) + \frac{L_i}{2}\log T + \log M_c$$

Model accuracy: $-\log p^T_{\hat{\boldsymbol{\theta}}(i)}(\boldsymbol{O})$; Model complexity: $\frac{L_i}{2}\log T$; constant (ignored): $\log M_c$

- $\boldsymbol{O}$: observation sequence
- $p^T_{\hat{\boldsymbol{\theta}}(i)}(\boldsymbol{O})$: maximum likelihood of $\boldsymbol{O}$ by i-th model
- L_i : model dimension of i-th model
- T : data length
- M_c : number of model candidates

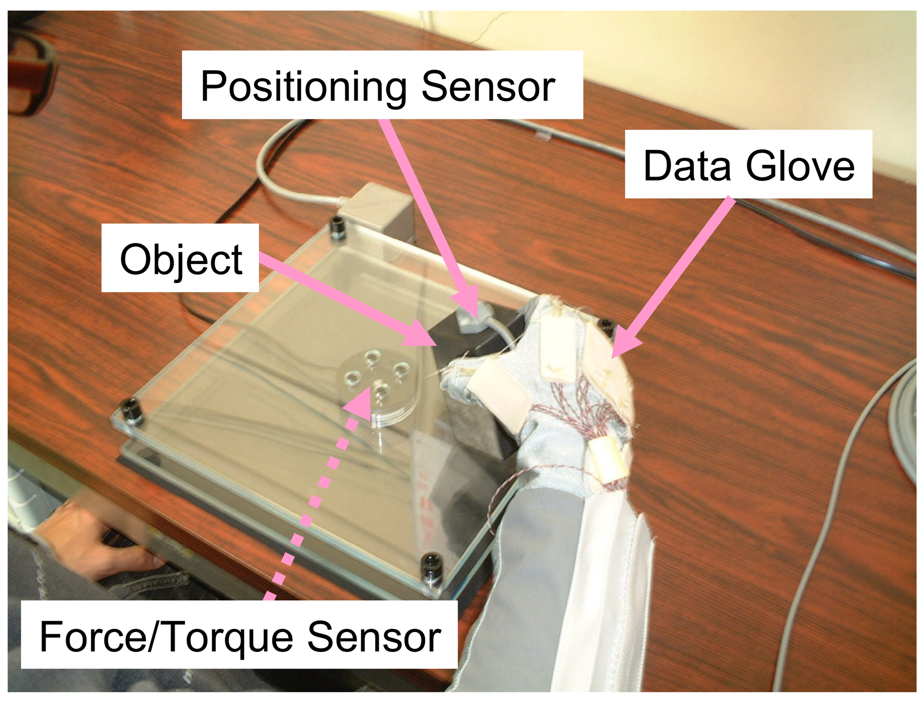
Application to HMM

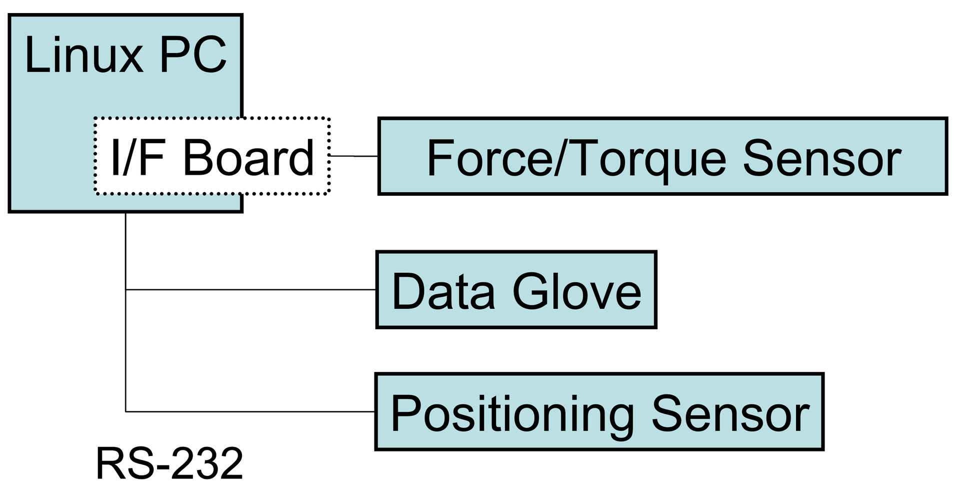
$$-\sum_k \log p(\boldsymbol{O}^{(k)}|\boldsymbol{\lambda}) + \frac{N^2 + (M-1)N + 2SMN}{2}\log\left(S\sum_k T^{(k)}\right)$$

- "Best" HMM topology can be determined with the MDL criterion

- $\boldsymbol{O}^{(k)}$: k-th observation sequence
- $p(\boldsymbol{O}^{(k)}|\boldsymbol{\lambda})$: likelihood of $\boldsymbol{O}^{(k)}$ by HMM $\boldsymbol{\lambda}$
- $T^{(k)}$: length of k-th observation sequence
- M : number of mixture components of pdf
- N : number of states
- S : number of elements of observation vector

Data Acquisition Setup



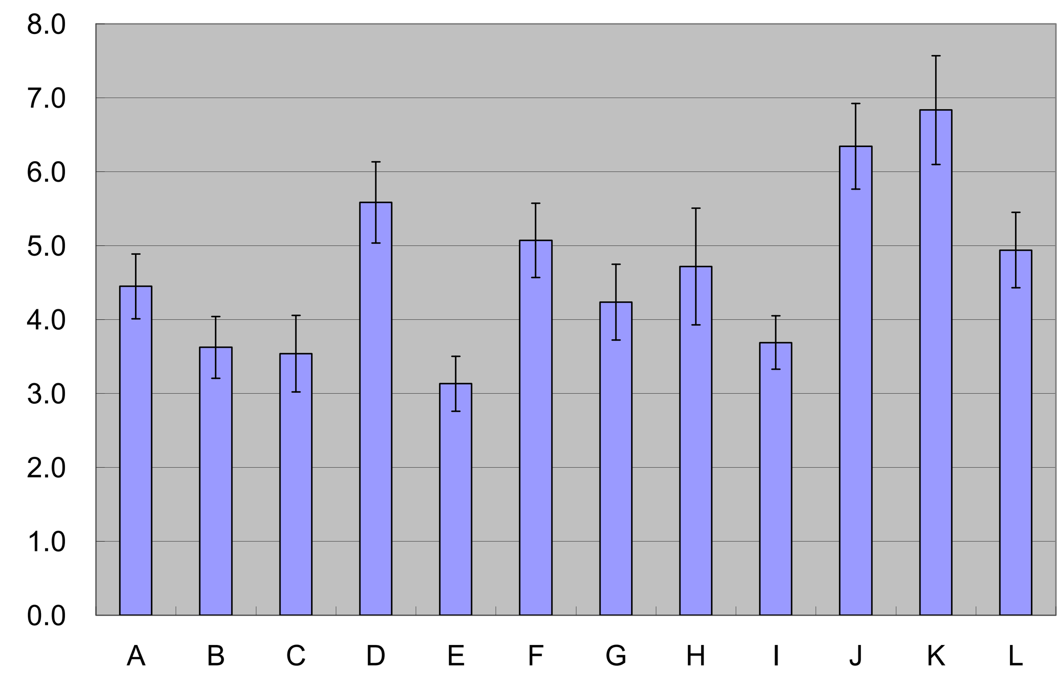


- Object: rubber cuboid
  - 50x50x100 [mm]
  - 0.36 [kg]: heavy to pick up by two fingers
- Sensors:
  - Data glove: Teiken StrinGlove (up to 24DOF)
  - Positioning sensor: Polhemus Fastrak (6DOF)
  - Force/torque sensor: Nitta (6-axis)
  - 120 [Hz] sampling

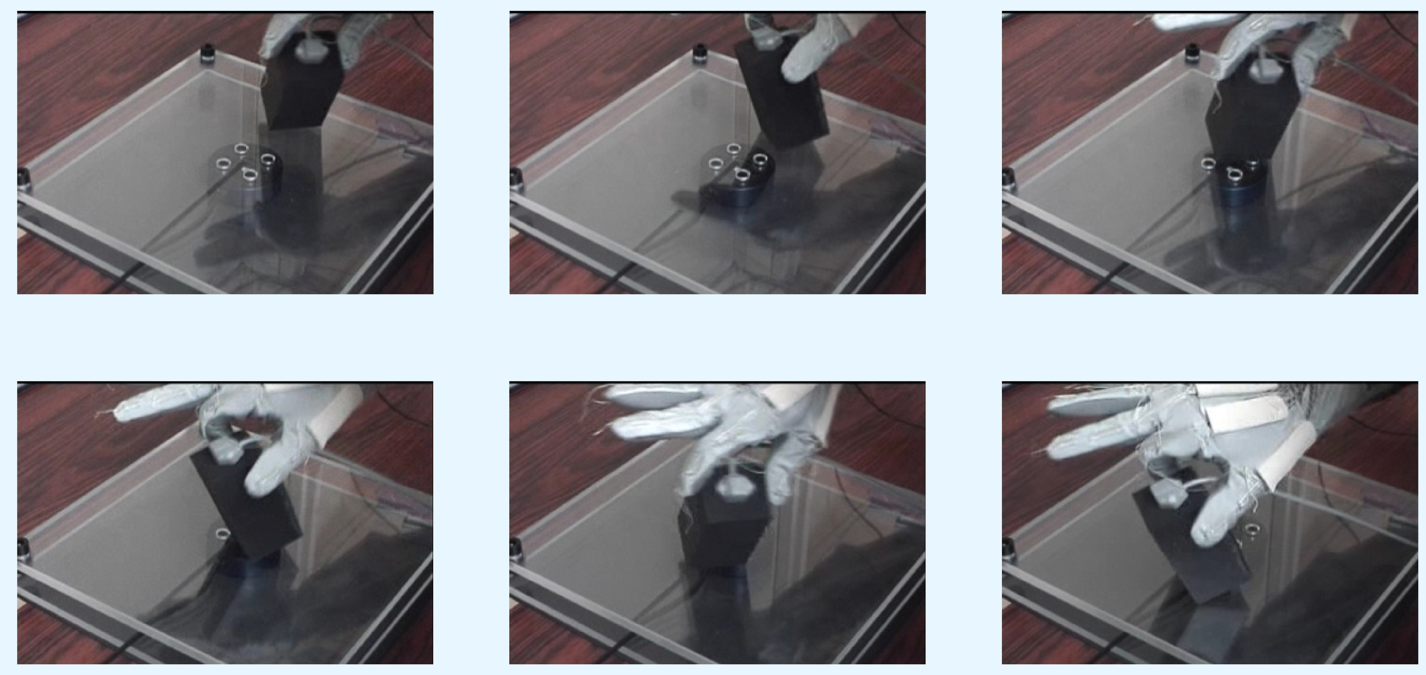
Experimental Results

Task

- 300 [mm] pivoting
  - as fast as possible
  - 12 male subjects (A-L)
  - 30 or more trials for each subject



Average Pivoting time [s]

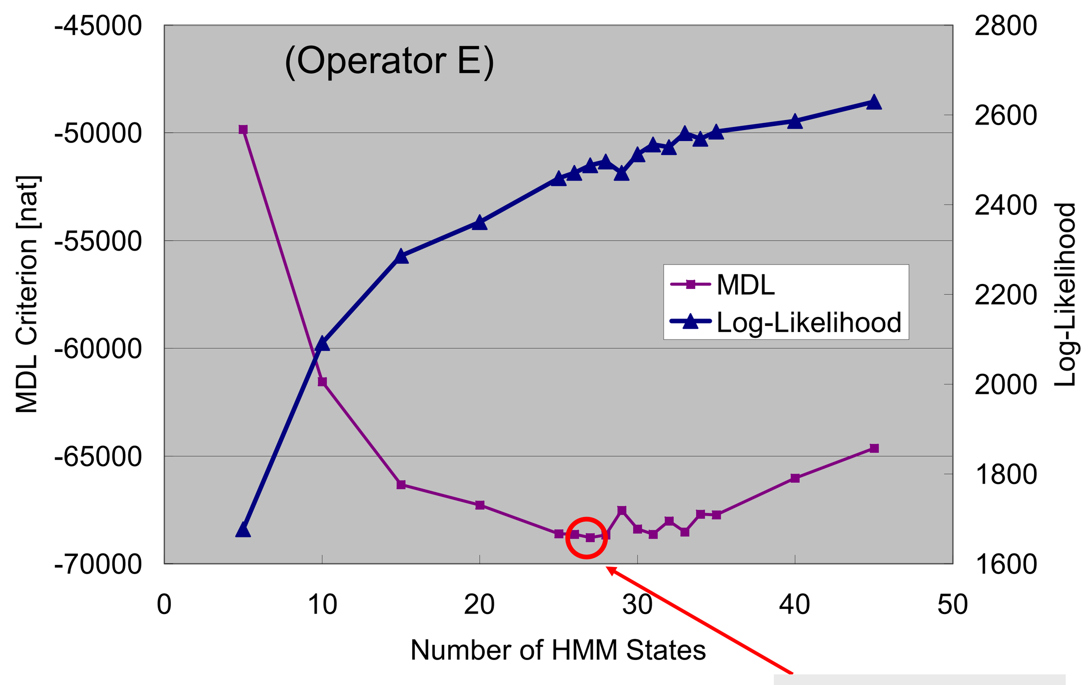


Scenes in Human Pivoting

- HMM symbols
  - Thumb: MP and IP flexion/extension
  - Index finger: MP, PIP and DIP flexion/extension
  - Ground reaction force in vertical axis

MDL-based topology determination

- Optimal number of HMM states is obtained



"Best" HMM

Obtained "Best" HMMs

operator	states	MDL [nat]
A	40	-1.11×10^5
B	35	-0.56×10^5
C	26	-0.32×10^5
D	32	-1.21×10^5
E	27	-0.69×10^5
F	35	-1.43×10^5
G	39	-0.52×10^5
H	40	-0.38×10^5
I	34	-0.76×10^5
J	49	-1.60×10^5
K	40	-1.66×10^5
L	39	-1.26×10^5

Dissimilarity Analysis

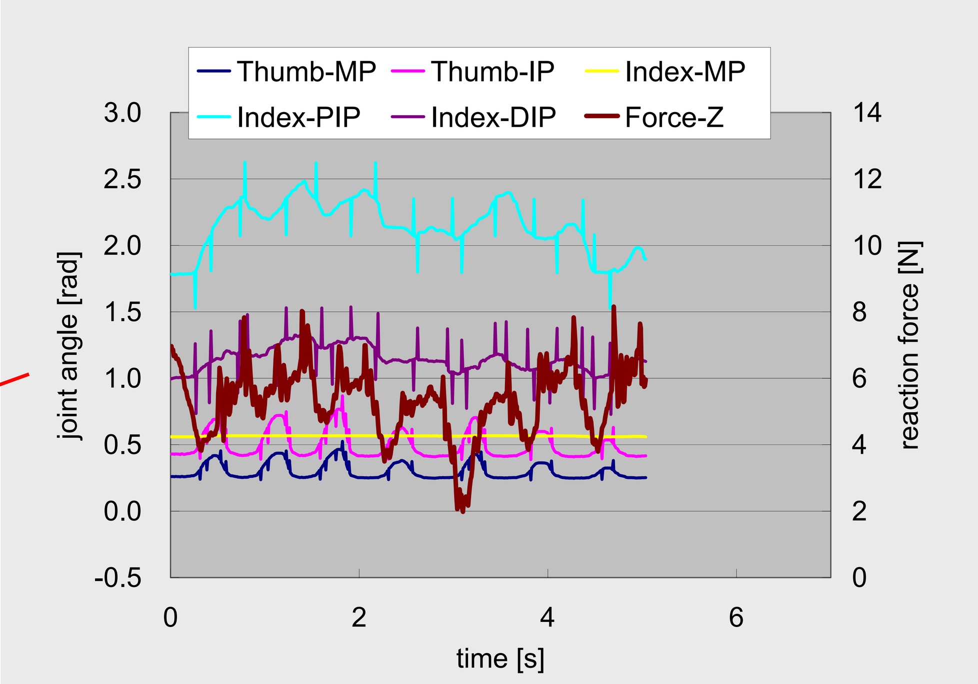
- A stochastic dissimilarity measure for HMMs [Rabiner 89]

$$D(\boldsymbol{\lambda}_i, \boldsymbol{\lambda}_j) = \frac{1}{K}\sum_{k=1}^{K} \frac{\log p(\boldsymbol{O}_i^{(k)}|\boldsymbol{\lambda}_i) - \log p(\boldsymbol{O}_i^{(k)}|\boldsymbol{\lambda}_j)}{T_i^{(k)}}$$

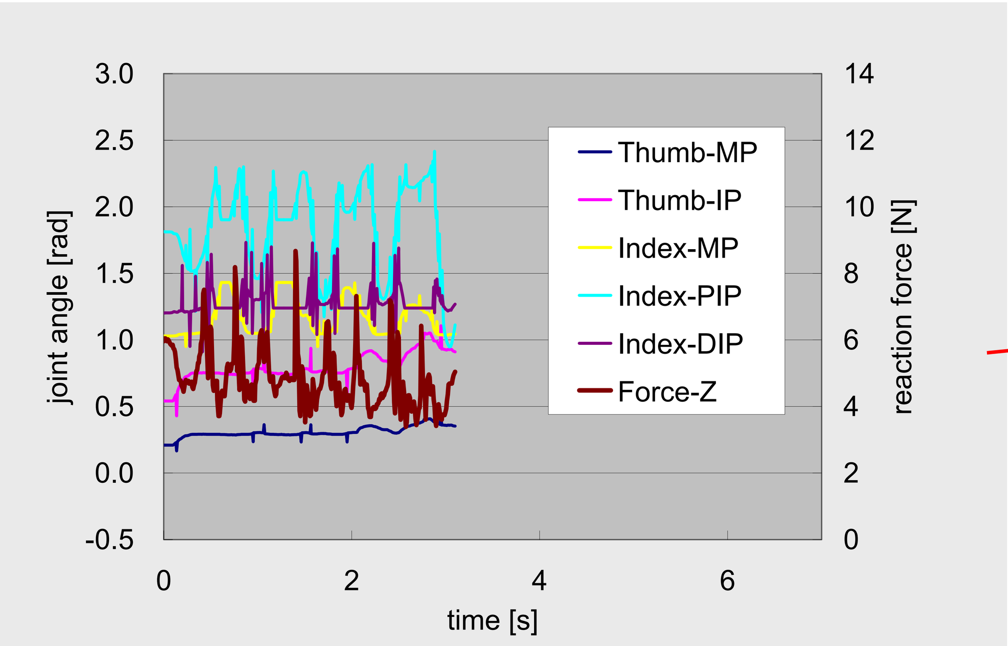
$$D_s(\boldsymbol{\lambda}_1, \boldsymbol{\lambda}_2) = \frac{1}{2}\{D(\boldsymbol{\lambda}_1, \boldsymbol{\lambda}_2) + D(\boldsymbol{\lambda}_2, \boldsymbol{\lambda}_1)\}$$

$O_i^{(k)}$: k-th observation sequence of i-th operator
$p(O_i^{(k)}|\boldsymbol{\lambda}_j)$: likelihood of $\boldsymbol{O}_i^{(k)}$ by HMM $\boldsymbol{\lambda}_j$
$T_i^{(k)}$: length of $\boldsymbol{O}_i^{(k)}$
K : number of observation sequences

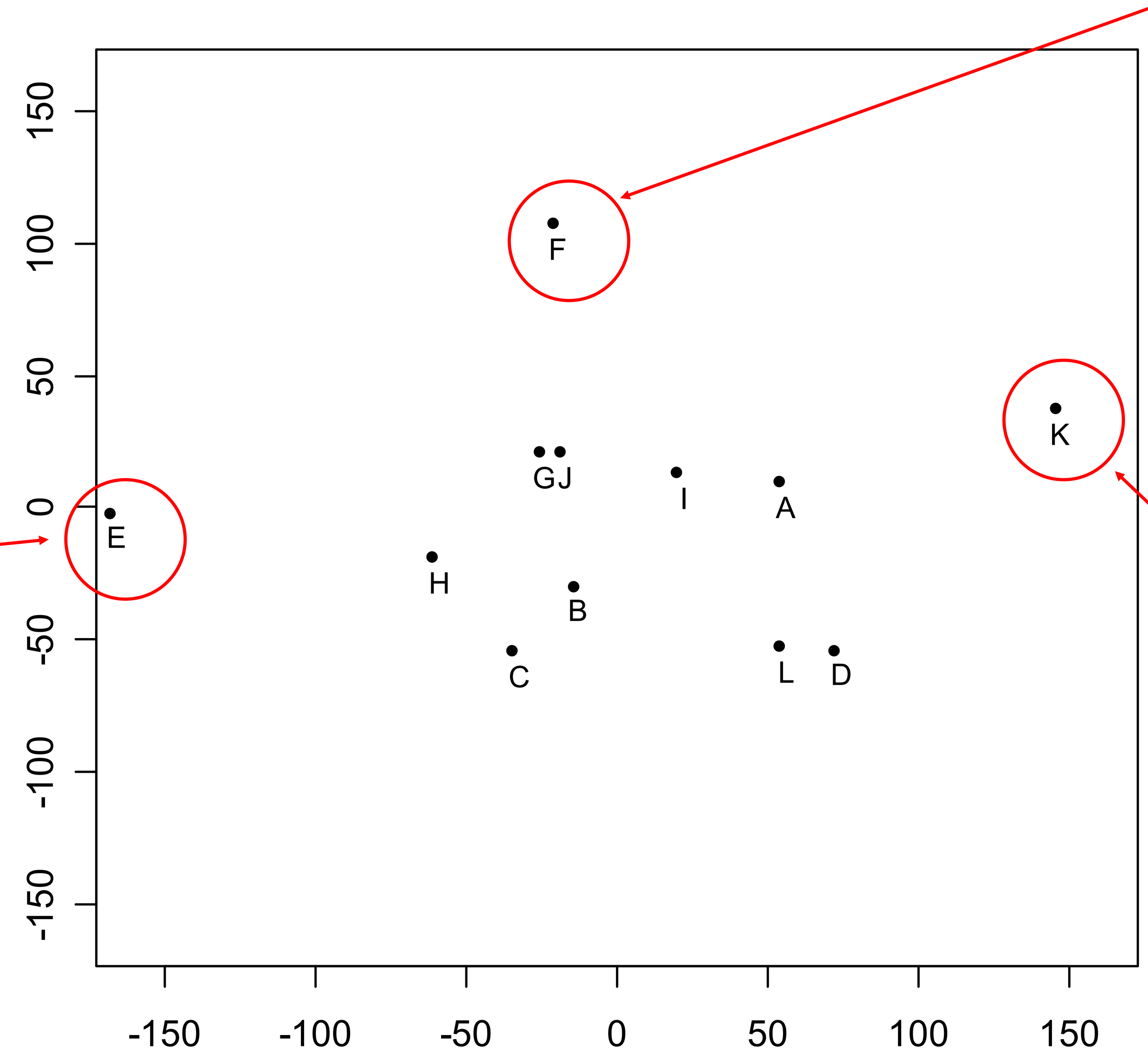
- Metric multidimensional scaling (MDS)
  - Plot HMMs on a plane to grasp dissimilarities easily
  - Features of individual manipulation are reflected in the plot



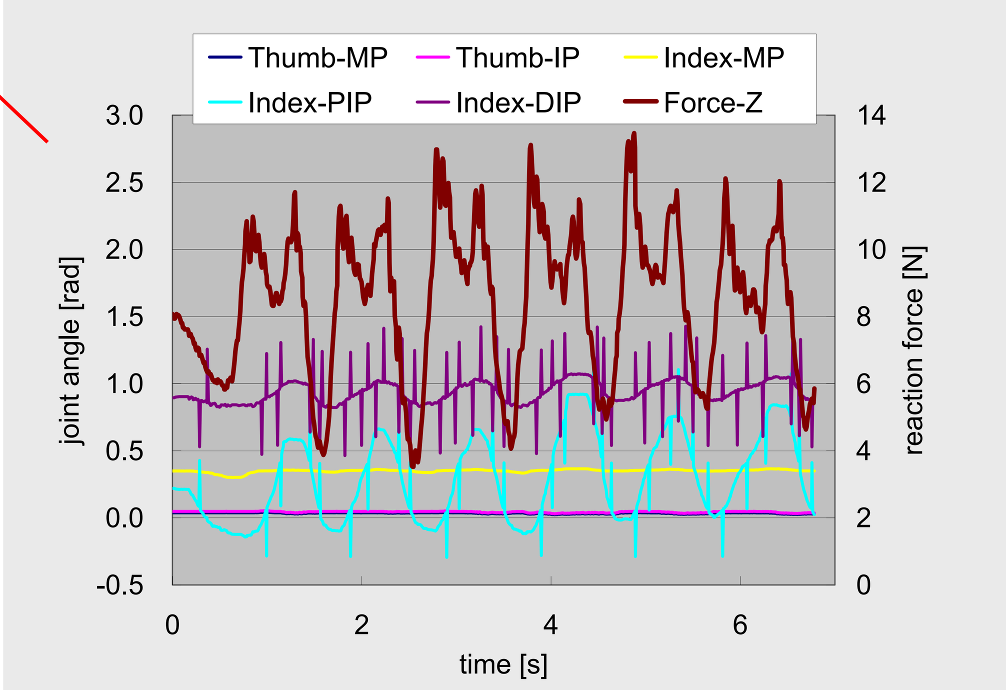
Operator F (typical)
• minimal use of MP flexion/extension of index finger



Operator E (typical)
• fastest manipulation



MDS results



Operator K (typical)
• slowest manipulation

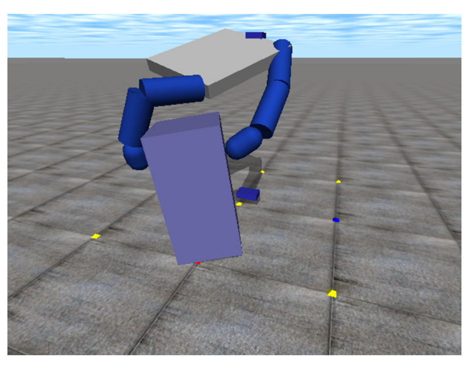
Conclusion

Summary

- An MDL-based hidden Markov modeling of human dexterous manipulation
  - applied to human pivoting operations
- Dissimilarity analysis that can be used to validate models of the internal mechanism behind human dexterity

Future work

- CPG-based modeling of human pivoting operations and its validation



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