Outcome Prediction of Hamstring Surgery in Patients with Cerebral Palsy via Bayesian Networks

Clinical Background
Cerebral Palsy is a neuro-motor condition that leads to a range of gait disorders, including crouch gait. Hamstring lengthening is a common procedure that can help patients with crouch gait walk in a more upright posture, but surgical outcomes vary across patients.

Children with crouch gait walk with excessive knee flexion

Surgery outcome measure: KneeScore is an indicator of crouch severity; average knee flexion angle during stance phase of gait

Study Goals
1. Predict which patients would benefit from surgery and the magnitude of expected improvement.
2. Identify key variables related to the evolution of patient post-surgical knee flexion.

Data
Our data consists of pairs of medical visits with surgery performed in between; we considered the left and right sides of a patient as separate training examples.

Visits include patient information such as age, clinical measurements such as strength assessment, and kinematic data in the form of 11 joint angles time series obtained during a gait cycle. All patients received multiple surgical operations. We split them into two groups: one received hamstring surgery, the other not.

Surgery group | # ex.
--- | ---
Hamstring | 442
No Hamstring | 1417

KneeScore distribution in Ham. surgery patients

We filtered out variables using a correlation threshold with KneeScore and a mutual correlation threshold between variables.

Motivation

Problem Setup
For a given patient, we predicted post-surgical KneeScore with a model trained on the 'Hamstring' population. We examined the same prediction computed by a model trained on the 'No Hamstring' population. We recommended the scenario yielding the best improvement.

Linear Continuous Bayesian Network
We trained a Linear Continuous Bayesian Network on each patient group. Variables are modeled as Gaussians and tied by linear relationships.

We adopted a knowledge discovery approach by learning network structure and parameters through the K2 algorithm. Starting from an initial node ordering, K2 looks for a structure that optimizes a regularized likelihood score. Number of parents per node is bounded.

The best performing initialization followed the order of correlation to the post-surgical KneeScore. We also tested random and Minimum Weight Spanning Tree initializations. Selected thresholds yield 37 variables; selected parents bound is 6.

Structure learning selected a small number of direct predicting variables: 2 for the 'Hamstring' model and 5.4 for the 'No hamstring' model, averaged on CV.

Both models selected a 'Popliteal Angle' variable and the 'Knee Flexion at maximum extension in the gait cycle'. Several variables were related to their opposite side equivalent in the graph.

Partial network structure of the 'Hamstring' model. The opposite side equivalent of a variable is denoted by the suffix 'opp'.

How Well Does the Model Predict Outcomes?

Can We Improve Surgical Decision-Making?
We used the models to predict hamstring surgery success on patients who received Hamstring lengthening. Operation is defined successful if it reduces the gap to the KneeScore for typically-developing children.

We compared our recommendations with the decisions of the clinical team. Test patients all received surgery, so the clinical team forecasted a success for all of them.

Conclusion and Next Steps
Our results suggest that our model could help the clinical team confirm their operation plans and reduce the incidence of patients who will show no improvement after surgery.

Next steps include leveraging the learned Bayesian network structure to introduce latent variables representing patient state over time or subpopulation, and investigating a setup with multiple surgery outcome variables.

References
Koller et al., "Learning Continuous Bayesian Networks", Proceedings of the Eighteenth Conference on Uncertainty in Artificial Intelligence, 2002
Seeger et al., Bayesian Networks for Clinical Decision Support in Lung Cancer Care, PLoS one, 2013
Brauburger et al, A new approach for Bayesian classifier learning structure via K2 Algorithm, Applied Artificial Intelligence, 2012
Scott et al., "Using Bayesian Networks to Predict Survival of Liver Transplant Patients", AAAI, 2005

In Ham. surgery patients:

- KneeScore ~ [10°, 40°]

- Typical KneeScore

- KF_maxExt

- KneeScore Post-surg.