What is Unique in Individual Gait Patterns?

Understanding and Interpreting Deep Learning in Gait Analysis

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Outline of the talk

- What is biomechanical gait analysis?
- Why is Machine Learning beneficial in biomechanical gait analysis?
- What we did learn from Machine Learning about human gait?
- **Study**: Explaining unique nature of individual gait patterns using Deep Learning
- Future perspectives for Deep Learning in biomechanical gait analysis
Biomechanical gait analysis - Joint Angles

Marker Set-Up

Motion Capturing

Model-Based Analysis

\( \varphi \circ \alpha \)

M J
Biomechanical gait analysis

What is unique in individual gait patterns?
Biomechanical gait analysis

**time-discrete vs. time-continuous**

[Schöllhorn et al. 2002]

**single vs. multiple variables**

ankle
knee
hip

[knee]

[Schöllhorn et al. 2002]

measurement devices

[Phinyomark et al. 2018]

“large” amount of data

[McKay et al. 2016]
Why is Machine Learning beneficial for biomechanical gait analysis?

Conventional gait analysis
- Single time-discrete variables
- “Subjective” pre-selection
- “Missing” information

Machine Learning
- Multiple time-continuous variables
- Holistic (full-body) analysis
What did we learn from Machine Learning about human gait?

**Aim:**

Classification of unique gait patterns to individual persons

Machine Learning in biomechanical gait analysis

Sample
n = 128 normal subjects (23.8 ± 9.1 years)
male = 76
female = 52

Protocol
informed consent
weighting
assignment of individual start position
5 test trials
10 analysis trials

Data acquisition
self-selected speed
barefoot

light barriers for speed control
4.5 m

ground reaction force
2 x Kistler force plate (40 x 60 cm ; 1000 Hz)
Machine Learning in biomechanical gait analysis

Data acquisition

- Self-selected speed
- Barefoot
- Light barriers for speed control
- Ground reaction force
- 2 x Kistler force plate (40 x 60 cm; 1000 Hz)

Data processing

- 1 x 606 vector of 3D ground reaction force of right and left stance phase
- 2. order Butterworth lowpass filter by 30 Hz
- Normed to body weight
- Time-normalized to 101 data points
- Z-transformed and scaled to a range of -1 to 1

Data analysis

- Classification: Support Vector Machines
- “Leave-one-out” cross-validation
- Liblinear Toolbox 1.4 (Fan et al., 2008)

128 subjects x 10 trials = 1280 gait vectors
Machine Learning in biomechanical gait analysis

What is unique in individual gait patterns?

Vertical ground reaction force [N/N]

Stance phase

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Machine Learning in biomechanical gait analysis

Initial observation

- Person identification: 99.8%
  (1278 of 1280 gait patterns)

- Chance level: 0.8%
  (1 of 128 persons)
Machine Learning in biomechanical gait analysis

follow-up (after 7-16 month)

person identification: 99.4%
(914 of 920 gait patterns)

chance level: 2.2%
(1 of 46 persons)
Machine Learning in biomechanical gait analysis

What did we learn from Machine Learning about human gait?

- gait patterns are unique to the individual (similar to other biometrics)
- long-term persistence of individual gait characteristics
- diagnoses [Simonsen & Alkjaer 2012] therapy [Schöllhorn et al. 2002] should respect individual persons rather than focus on stereotypes and normal data
Machine Learning in biomechanical gait analysis

What did we learn from Machine Learning about human gait?

- **Individual** [Schöllhorn et al. 2002; Horst et al. 2017; Costilla Reyes et al. 2018; Connor & Ross 2018]
- **Age** [Fukuchi et al. 2011; Eskofier et al. 2013; Li et al. 2018]
- **Gender** [Begg & Kamruzzaman 2005; Eskofier et al. 2013; Andrade et al. 2013]
- **Fatigue** [Jäger et al. 2003; Janssen et al. 2011]
- **Emotions** [Janssen et al. 2008; Roether et al. 2009; Gross et al. 2012]
- ...
Machine Learning in biomechanical gait analysis

What is unique in individual gait patterns?

Gait analysis
- cameras
- Lower-Body Joint Angles
- Ground Reaction Force
- force plates

Pathological gait conditions like:
- Lower limb fractures [Holzreiter & Köhle 1993; Figueiredo et al. 2018]
- Anterior cruciate ligament injury [Christian et al. 2016]
- Arthrosis [Lafuente et al. 1997; Wu & Su 2000]
- Hallux valgus [Barton & Lees 1995]

(Neurological) disorders like:
- Cerebral palsy [Barton 1999]
- Parkinson’s disease [Zeng et al. 2016]
- Multiples scleroses [Alaqtaash et al. 2011]
- Traumatic brain injuries [Williams et al. 2015]
Machine Learning in biomechanical gait analysis

What is unique in individual gait patterns?

Aim: Understanding und interpreting Deep Learning in gait analysis

Objective: Uniqueness of individual gait patterns
Methods

Gait analysis
10 x camera (Qualysis, 250 Hz)

2 x force plate (Kistler, 1000 Hz)

Sample
male = 28
female = 29

n = 57 subjects
(23.1 ± 2.7 years)

Machine Learning
DNN

Black Box

What is unique in individual gait patterns?

Classification

Methods

Machine Learning

ANN ; SVM ; RFC

Gait analysis

Cameras

force plates
Layer-Wise Relevance Propagation (LRP)

Bach S et al. 2015. PLOS One, 10(7), e0130140.

Idea: Decompose function

\[ \sum_i R_i = f(x) \]

Input \( x \)

Explain prediction

(how much each pixel contributes to prediction)

Classifier

Rooster

Prediction \( f(x) \)

Machine Learning

DNN

Subject

Black Box

LRP
Methods

**Gait analysis**

10 x camera (Qualysis, 250 Hz)

2 x force plate (Kistler, 1000 Hz)

**Machine Learning**

DNN

LRP

*Classification Methods*

- Machine Learning
  - ANN
  - SVM
  - RFC

*Gait analysis*

- Cameras
- Force plates

*Subject*

10 x camera (Qualysis, 250 Hz)

2 x force plate (Kistler, 1000 Hz)

*Gait feature relevance*
Results

Subject 6

GRF Input

GRF Relevance

Subject 6

LBJA Input

LBJA Relevance

no single variable
Results

Subject 6

GRF Input

GRF Relevance

Subject 6

LJIA Input

LJIA Relevance

no single variable
plausible features
What is unique in individual gait patterns?

Results

Subject 6

Subject 21

Subject 28

Subject 42

no single variable

plausible features

left / right symmetries
Future perspectives for Deep Learning in gait analysis

- **Understanding and interpreting** in clinical gait classification

- **Pretrained models for gait patterns**
  - Biomechanical data collection of large, balanced numbers of samples, subjects and classes under standardized conditions is time-consuming

- **Public gait database**
  - Small number of public datasets of biomechanical gait patterns available
  - Heterogeneous experimental protocols, different model variables, different measurement devices and data formats between the individual data sets, which are difficult to combine
Public datasets


GitHub
