Analysis of Movement Smoothness

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Winter School in Computational Neurorehabilitation,
Obertauern 2014, Mini-Project G
Experiment Setup
(pointing task)
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- Mechanical
  - MIT - Manus [Hogan et al. 1992]
  - ARMin [Nef et al. 2006]
- IMU based
  - Arm and hand rehabilitation [Luo et al. 2011]
  - Xsens MVN suite, full body [Roetenberg 2009]

Fig. 3. Evolution of movement path and smoothness for two stroke subjects and a healthy subject. The first row displays the reaching movement paths performed by these subjects at the start and end of the experiment. The following rows display the evolution of smoothness as quantified by the different smoothness measures analyzed in the study. The left and middle column display the evolution of movement smoothness with therapy for a mild stroke subject (left column), and a severe stroke subject (middle column) as a function of the therapy session, respectively. The right column shows the evolution of smoothness for a healthy subject undergoing a motor learning experiment as a function of the experiment block number. The plots show the mean, median, and the interquartile range of the smoothness values calculated for the movements performed to all the different target locations shown in the first row. By carrying out a Mann-Whitney U test (at 5% significance level) to compare the medians of the first five therapy sessions with that of last five therapy sessions, we found that \( \eta_{pm} \), \( \eta_{dl} \), \( \eta_{ldl} \), \( \eta_{spal} \) and \( \eta_{sal} \) improved significantly for the mild stroke subject. For the severe stroke subject, the only measure that showed a significant increase in smoothness was \( \eta_{sal} \).
Experiment Setup
(pointing task)

[Image -445x-1267 to 1753x573]

Stroke patient
(mild hemiparesis)

Stroke patient
(severe hemiparesis)

[Balasubramanian and Melendez-Calderon 2011]
Minimum Square Jerk

\[ J = -\frac{1}{2} \int_{t_1}^{t_2} j^2(t) dt \]  

[Flash, Hogan 1984]
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[Balasubramanian and Melendez-Calderon 2011]
Dimensionless jerk (DLJ) [Hogan and Sternard 2009]

\[ J_{DLJ} = \int_{t_1}^{t_2} j(t)^2 \, dt \frac{D^3}{V^2} \]

- Duration
- Mean or peak velocity
Dimensionless jerk (DLJ) [Hogan and Sternard 2009]

\[ J_{DLJ} = \int_{t_1}^{t_2} j(t)^2 dt \frac{D^3}{V^2} \]

- Duration
- Mean or peak velocity

‘ceiling effect’ [Balasubramanian and Melendez-Calderon et al 2011]
Log DLJ

\[ J_{DLJ} = \log(J_{DLJ}) \]  [Balasubramanian and Melendez-Calderon et al 2011]
Root DLJ

\[ J_{RD LJ} = \sqrt{J_{DLJ}} \]
Root Mean Square Jerk (RMSJ)

\[ J_{RMSJ} = -\sqrt{\frac{\int_{t_1}^{t_2} j^2 dt}{D}} \]
Numbers Of Speed Peaks

[Rohrer et al 2002] [Teo et al 2002]
Spectral Arc Length

[Balasubramanian and Melendez-Calderon et al 2011]
Overview

data from [Balasubramanian and Melendez-Calderon et al 2011]
Smoothness Metric should be

- dimensionless
- montonic response
- robust to noise (3rd derivative!)
- sensitive in the physiological range (no ceiling)
\[ v(t) = \sum_{k=1}^{N_s} A_k m \left( \frac{t - \Delta T_k}{T_k} \right) \]
How about Accelerometers?
How about Accelerometers?

\[ J_{DLJ} = \frac{1}{D^3} \int_{t_1}^{t_2} j(t)^2 dt \frac{V^2}{V^2} \]

- Duration
- Mean or peak velocity
How about Accelerometers?

Smoothness Assessment

Intuitive and common assessment criterion for pointing tasks, which reflects the patients impairment level.

- "Movement smoothness changes during stroke recovery" [Rohrer 2002]
- Dimension-less Jerk (DLJ) is a "shape based" metric [Hogan and Sternad 2009]
- [Balasubramanian et al. 2011] claim that DLJ [Hogan and Sternard 2009] shows "ceiling effect"
- Number of zero acceleration crossings "unsuitable"
- Introduce "Spectral Arc Length", a Fourier analysis based metric

III) Smoothness

We can use it to compute the forward kinematics for the whole joint space trajectory.

\[
J_{DLJ} = \int_{t_1}^{t_2} j(t)^2 dt \frac{D^3}{V^2}
\]

\[
J_{ACC} = -\int_{t_1}^{t_2} j^2 dt \frac{D}{A_{max}^2}
\]
Conclusion

• For positional data (e.g. robot) there is no standard yet but NOP, LDLJ and SAC seem suitable and are popular

• Simulations are a powerful tool to show the limitations of smoothness metrics

• For other types of kinematic data (IMUs) suitable metrics are not established yet