Musculoskeletal modelling: EMG-Driven models

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From brain to muscle activation

Motor unit = anterior horn cell + nerve fibre + muscle fibre

Meaningful information
EMG-Driven models

• Philosophy: Mechanically-based objective functions failed in generating adequate muscular activations for a large variety of tasks and/or population

• Two directions:
  – Bounding the solution space using EMG data
  – Using EMG data as input to estimate the muscular activations
Bounding the solution space

• The recorded EMG is used as constraint of the optimization procedure

\[ G(t) = \sum_{i}^{i} \left( \frac{t_i}{PCSA_i} \right)^2, \]

• \( t_i \) or \( t_m \) stand for the muscle tensions with additional constraints:

\[ (1 - \mu)t_{m\text{EMG}} \leq t_m \leq (1 + \mu)t_{m\text{EMG}}, \quad \text{with } 0 \leq \mu \leq 0.05 \]

Vigouroux et al., 2007
Bounding the solution space

- EMG-constrained muscle forces are closer to experimental activations, particularly for antagonist muscles

- Efficient procedure, but limited to quasi-isometric contractions

Vigouroux et al., 2007
Basic principles

- System dynamics
  - $j = 1:m$ muscles
  - $k = 1:p$ DoFs
  - $l = 1:r$ joint reactions

![Diagram showing muscle dynamics](image)

Muscle excitation
Muscle activation
Musculo-tendon forces
Ligament and contact forces
Skeletal dynamics
Kinematics parameters

EMG data

Courtesy of R. Dumas
EMG to activation Processing

• From raw data to activation: 4 steps

  – Rectification

  – Low-pass filtering: Butterworth zero time lag, cut-off freq $\approx 5\,Hz$

  – Activation dynamics step

  – Non-linearization step
Activation dynamics

- General expression of a recursive filter to represent the influence of previous « activation states » on the current activation, $u(t)$

$$u(t) = \alpha e(t - d) - \beta_1 u(t - 1) - \beta_2 u(t - 2)$$

- $d = \text{Electromechanical delay}$
- $\beta_1$ and $\beta_2$ represent the activation dynamics coefficients
Non-linearization

- Force is non-linearly related to activation, even for isometric tasks

\[ a(t) = \frac{e^{AU(t)} - 1}{e^A - 1} \]

- A factor stands for the shape factor
Forward-Inverse EMG-Driven model

Gérus et al., 2011, 2012
Hill-type model

Series Elastic Element (SEE)

TENDON - APONEUROSIS

Force-length relationship
Active component

Force-velocity relationship

α: pennation angle

MUSCLE FIBER

Concentric element

Parallel elastic element

Passive component

Zajac (1989)

Normalized fiber length

Normalized force

Normalized fiber shortening velocity

Normalized force

Concentric
Eccentric

Normalized fiber shortening velocity

Normalized force

Normalized fiber length

Normalized force

Normalized fiber shortening velocity

Normalized force

Normalized fiber shortening velocity
Forward-Inverse EMG-Driven model

Input

EMG

Activation Dynamics

Contraction Dynamics

Muscle Force

Musculo-skeletal geometry

Muscle Moment

\[ \sum \]

Moments comparison

Simulated Annealing (global minimum)

Gérus et al., 2011, 2012

Mouvement

OR

Recorded by torquemeter
EMG-Driven model

Gérus et al., 2011, 2012

Muscle Force

Musculo-skeletal geometry

Multi joint Dynamic

Muscle Moment

EMG

Input

n Muscles

Activation Dynamics

Contraction Dynamics

Mouvement

Recorded by torquemeter
Parameters to optimize

- Those related to the EMG-processing:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Variable</th>
<th>Bounds</th>
<th>Applied to</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta_1 ) &amp; ( \beta_2 )</td>
<td>Filter coefficients</td>
<td>(-0.8 &lt; \beta_1 ) &amp; ( \beta_2 &lt; 0.95 )</td>
<td>Each muscle</td>
</tr>
<tr>
<td>d</td>
<td>Electro-mechanical Delay</td>
<td>(10\text{ms} &lt; d &lt; 80\text{ms} )</td>
<td>Each muscle</td>
</tr>
<tr>
<td>A</td>
<td>Shape factor</td>
<td>(0.01 &lt; A &lt; 0.1 )</td>
<td>Each muscle</td>
</tr>
</tbody>
</table>
Parameters to optimize

- Those related to the Hill-type muscle model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Bounds</th>
<th>Applied to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Fiber Length</td>
<td>OFL ± 5%</td>
<td>Each muscle</td>
</tr>
<tr>
<td>Tendon Slack Length</td>
<td>TSL ± 5%</td>
<td>Each muscle</td>
</tr>
<tr>
<td>Slope of the OFL/activation line</td>
<td>$0 &lt; \lambda &lt; 0.25$</td>
<td>Each muscle</td>
</tr>
<tr>
<td>Gain factor</td>
<td>$0.5 &lt; G &lt; 2$</td>
<td>Each muscle group</td>
</tr>
</tbody>
</table>
Why include EMG data?

- EMG data collection and processing is rather « boring » with lots of experimental issues (skin preparation, electrode positionings, crosstalk effects...)

- Data collection is limited to superficial muscles (thus sometimes poorly representing the real pattern of activations)

- Adding parameters in an optimization procedure is never a good idea

BUT!
Why include EMG data?

Can such activations be generated by the same energetically-based criterion?

Diabetic patients and control subjects muscular activations during gait (Kwon et al., 2003)
Why include EMG data?

- To be as close as possible to the real activations generated by the subject (even unbalanced and/or unnatural ones) and have an increased « trust » in the input data.

- To be able to estimate muscle forces even for tasks where classical cost functions (energetically based for example) are not applicable.

- To get individualized strategies to cope with pathology and/or impairment (Shao and Buchanan, 2008 for stroke patients).
Actual developments

• How to avoid numerous recordings and guide deep muscles activations creation?

• Muscle synergies represent how muscles are assembled as functional groups to achieve a goal-directed task.

\[
E = WC + e \\
\min_{W \geq 0, C \geq 0} \| E - WC \|_{FRO}
\]

E = EMG matrix
W = muscle weightings
C = time-varying profiles

• Usually done using Non Negative Matrix Factorization (NNMF)
Muscle synergies

Clark & Ting, 2010
Muscle synergies

A  synergy activation coefficients

mean $r_{\text{max}} = 0.93$

mean $r_{\text{max}} = 0.95$

mean $r_{\text{max}} = 0.97$

% of pedaling cycle

B  muscle synergy vectors

mean $r = 0.97$

mean $r = 0.99$

mean $r = 0.98$

muscles

Hug et al., 2011
Actual developments

Sartori et al., 2013
Other possible ideas to bound the solution space

- EMG-EMG Coherence
- Functional Connectivity Dynamics

Charissou et al., 2016

Vernooij et al., In revision
limits

• Emg-to-force relationship for pathology is not known (Serge, Bohnes 2016 for CP) BUT it’s less than likely that a CP kid moves following an energetically-based criterion

-> « EMG-helped » procedures are needed

• Input data (tendon properties, fiber geometry), activation dynamics, joint geometry, objective functions -> Florent
Conclusion

• Up to now, EMG-Driven models allows to include subject- or task- specific activation data to estimate muscle forces

• Cumbersome process, but unequalled results

• Actual developments tend to simplify the procedure by treating muscles as « goal-dependant functional groups »

• Few data available on neurologically impaired EMG-Force relationships
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