Appendix A

Simulation of forward dynamics

The simulation flow of the forward dynamics of OpenSim simulator is shown in Figure 1. As an input we provide muscle activation over some period of time. Based on these activations muscles tendon dynamics are produced. Calculated forces are applied depending on the geometry of the model and moments are calculated. Movements are produced by considering multi-body interactions.

![Figure 1. Simulation flow of the forward dynamics](http://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/935912/)

Musculoskeletal model dynamics

We describe the accelerations as inertia and forces applied to our biomechanical model (represented as a set of rigid bodies) from the second Newton’s law:

\[
\ddot{\mathbf{q}} = [\mathbf{M}(\mathbf{q})]^{-1}(\tau + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \mathbf{f}),
\]

(1)

where \(\ddot{\mathbf{q}}\) is the coordinate accelerations, \(\tau\) is the vector of joint torques, \(\mathbf{c}(\mathbf{q}, \dot{\mathbf{q}})\) is the vector of Coriolis and centrifugal forces, as a function of coordinates, \(\mathbf{q}\), and their velocities, \(\dot{\mathbf{q}}\), \(\mathbf{g}(\mathbf{q})\) is the vector of gravity, \(\mathbf{f}\) is the vector of other forces applied to the model and \([\mathbf{M}(\mathbf{q})]^{-1}\) is the inverse of the mass matrix.

Moments due to the muscle forces are calculated as:

\[
\tau_m = [\mathbf{r}(\mathbf{q})]f(a, l, \dot{l}),
\]

(2)

where \(\mathbf{r}(\mathbf{q})\) are moments arms, \(f\) is the function of muscle activations, \(a\) - activations, \(l\) - fiber lengths and \(\dot{l}\) - fiber velocities.

Muscle tendon dynamics

In our simulations we used the Millard muscle model – the modified Hill-type model implemented in OpenSim. This model consists of an active contractile element (CE), a passive elastic element (PE) and an elastic tendon (TE) (see Figure 2).

![Figure 2. Schematic representation of a muscle model](http://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/935912/)

The force generated by a muscle depends on its length as represented by the active-force-length curve \(f_L(l)\) having a peak of a force of \(f_0\) at a length \(l_0\). During muscle contractions, the produced force depends non-linearly on its rate of lengthening represented by the force-velocity curve \(f_V(v)\). If the muscle is stretched beyond some threshold length it produces an elastic force which is represented by the passive-force-length curve \(f_{PE}(l)\). The total force generated by the muscle is calculated as:

\[
F = f_0(a f_L(l)) f_V(v) + f_{PE}(l),
\]

(3)

where \(a\) is the muscle activation, which ranges from 0 to 1.
Appendix B

Calculation of metabolic costs

For the calculation of the metabolic costs we used the built-in functionality of the OpenSim simulator based on the work of Umberger (Umberger et al., 2003). Muscle metabolic consumption is assumed to be the sum of heat rates and a mechanical work rate, all measured in Watts (W):

\[ \dot{E} = \sum_{\text{all muscles}} (\dot{A} + \dot{M} + \dot{S} + \dot{W}). \]  

(1)

where \( \dot{A} \) is the activation heat rate, \( \dot{M} \) is the maintenance heat rate, \( \dot{S} \) is the shortening heat rate and \( \dot{W} \) is the mechanical work.

The activation and maintenance heat rates are calculated as follows:

\[ \dot{A} + \dot{M} = \begin{cases} 
(128 (1 - r) + 25) A^{0.6} S, & l_{CE} \leq l_{CE,\text{opt}} \\
(0.4 (128 (1 - r) + 25) + 0.6 (128 (1 - r) + 25) F_{CE,\text{ISO}}) A^{0.6} S, & l_{CE} > l_{CE,\text{opt}} 
\end{cases} \]  

(2)

\[ A = \begin{cases} 
(u, u > a) / 2, & u \leq a 
\end{cases} \]  

(3)

where \( m \) is the mass of the muscle (kg), \( l_{CE} \) is the muscle fibre length at the current time, \( l_{CE,\text{opt}} \) is the optimal fiber length of the muscle, \( F_{CE,\text{ISO}} \) is the normalized contractile element force-length curve, \( u \) is the muscle excitation, \( a \) is the muscle activation and \( s \) is aerobic/anaerobic scaling factor.

The shortening heat rate is calculated as follows:

\[ \dot{S} = \begin{cases} 
m \left( \begin{array}{c}
\left(\alpha_l v_{CE,\text{norm}}^2\right) + \left(\alpha_f v_{CE,\text{norm}}^2\right)
\end{array} \right), & l_{CE} \leq l_{CE,\text{opt}} \\
m \left( \begin{array}{c}
\left(\alpha_l v_{CE,\text{norm}}^2\right) + \left(\alpha_f v_{CE,\text{norm}}^2\right)
\end{array} \right), & l_{CE} > l_{CE,\text{opt}} \\
m \left(\alpha_l v_{CE,\text{norm}}^2\right), & l_{CE} \leq l_{CE,\text{opt}} \\
m \left(\alpha_l v_{CE,\text{norm}}^2\right), & l_{CE} > l_{CE,\text{opt}} 
\end{cases} \]  

(4)

\[ A = \begin{cases} 
(u, u > a) / 2, & u \leq a 
\end{cases} \]  

(5)

where \( m \) is the muscle of the mass (kg), \( l_{CE} \) is muscle fiber length at the current time, \( l_{CE,\text{opt}} \) is optimal fiber length of the muscle, \( F_{CE,\text{ISO}} \) is normalized contractile element force-length curve, \( u \) is muscle excitation, \( a \) is muscle activation, \( s \) is aerobic/anaerobic scaling factor, \( v_{CE,\text{norm}} \) is normalized muscle fiber velocity and \( v_{CE} \) is muscle fiber velocity at the current time.

The mechanical work rate is calculated as follows:

\[ \dot{W} = -(F_{CE} v_{CE}), \]  

(6)

where \( v_{CE} \) is muscle fiber velocity and \( F_{CE} \) is a force developed by a contractile element of muscle at the current time.
Appendix C

Parameters of CMA-ES

The behavior of the CMA-ES algorithm strongly relies on its parameters. The number of objective variables is equal to the number of muscles, \( N = 6 \). The initial values for the objective variables is equal to the possible minimum activation level of the muscles of 0.05. The step-size of the algorithm used for the sampling of the new solution sigma equals 1.0. The acceptable threshold for the difference between current and searched solutions equals to 1.5, \( \text{stopfitness} = 1.5 \). Limit for the number of iterations set to 2500, after reaching the limit, if no feasible solutions have been found, the algorithm starts with different random seed. Resulting muscle activations for different eye gaze positions can be found in supplementary materials.