

How to compute OpenSim's muscle moment arm with Simbody

Michael Sherman, 19 Oct 2010

OpenSim provides to its biomechanics users a calculation called “muscle moment arm” which captures to some degree the leverage of a particular muscle with respect to a particular joint, while in a particular configuration. For simple cases, this is the same as the conventional moment arm calculation in mechanical engineering. A straight-line muscle whose origin and insertion points connect two adjacent bodies connected by a pin joint is the simplest case. In practice, however, muscle may span several joints (wrist, neck, spine) and will follow contorted paths crossing over various curved bone surfaces. For these situations we need a careful definition of “muscle moment arm” that is analogous to the mechanical engineering concept and of use to biomedical researchers.

There are other related quantities that can easily be confused with moment arm, such as the amount of joint acceleration that a muscle can produce. That will be equivalent to moment arm in simple cases but confusingly different in more complex situations. Here we will give a precise definition of what we mean by “muscle moment arm” and, given that definition, how that quantity may be efficiently calculated. We will not attempt to address any deeper questions such as when you should be interested in moment arm or how you should use it.

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Assumptions

A muscle is considered to connect body A to body B via a minimum-length curved path connecting an “origin” point on body A to an “insertion” point on body B, possibly passing frictionlessly over wrapping surfaces on these or other bodies. No particular connectivity is assumed for these bodies in the multibody model of the skeleton. For example, there might be a patella with wrap surface hanging off one of the bodies and driven from an arbitrary mobility.

Assumption 1: Although the path includes both muscle and tendon segments whose relative lengths vary dynamically, we are assuming that the total length l is just a kinematic quantity $l(q)$ (typically representing the shortest path) that can be calculated once the poses of all the bodies are known via specification of the generalized coordinates q . So for any given muscle we assume

$$l = l(q) \quad (1)$$

It is critical that any motion of points at which the muscle applies forces be modeled in a physically realizable manner so that muscle forces do the appropriate amount of work. (OpenSim’s “moving muscle point” feature appears to violate this requirement.)

Assumption 2: Force generation by the muscle is completely characterized by a scalar tension $s \geq 0$ acting uniformly along the path, such that the set of spatial forces^{*} F applied by the muscle in a given configuration is just a linear function of s :

$$F(s) = Ts \quad (2)$$

where $T=T(q)$ is the muscle’s instantaneous “force transmission matrix”. We expect that a muscle element can efficiently compute F given s , although T is not explicitly available.

Brief background

A few details are necessary for the derivation below.

1. Generalized speeds u are not always the same as time derivatives \dot{q} of the generalized coordinates q , although they are closely related. This distinction will be important below because generalized forces are dual to the generalized speeds, but not to the generalized coordinate derivatives. In Simbody, the relationship is given by a block diagonal matrix $N(q)$:

$$\dot{q} \triangleq \frac{dq}{dt} = Nu \quad (3)$$

^{*} A spatial body force F^B is a pair of vectors: a moment applied to body B and a force applied at the body B origin; F here is a stacked vector of such spatial body forces.

2. There is a dual relationship between forces and velocities when measured in the same basis. The portion of a body B 's spatial velocity V^B (at B 's origin) due to generalized speed u_i is:

$$V_i^B = \frac{\partial V^B}{\partial u_i} u_i = J_i^B u_i \quad (4)$$

where Jacobian $J_i^B = J_i^B(q)$, and $V^B = \sum V_i^B$. The dual of this relationship relates a spatial force F^B applied at body B 's origin to the generalized force f_i :

$$f_i = (J_i^B)^T F^B \quad (5)$$

and $f = \sum f_i$. For the dual relationship to hold, the generalized speeds and forces must be expressed in the same generalized basis.

Definition of “moment arm”

Moment arm is a property of a given muscle about a particular angular quantity of interest we'll call θ , measured at a particular configuration q of the multibody system. It is a scalar geometric quantity $r=r(q)$, with units of length. r relates an infinitesimal change in muscle length l to the corresponding unitless change in angle θ , via the definition

$$r = \frac{dl}{d\theta} \quad (6)$$

Moment arm is defined only for angles θ which determine muscle length l kinematically, that is, we expect a virtual displacement $d\theta$ to produce a virtual length change dl that depends only on q , not on velocities, forces, or masses. All generalized coordinates q that can affect θ are thus assumed to be coupled; any that are not coupled explicitly by a constraint will be held constant during the moment arm calculation (that is, they are “coupled” with a coupling factor of 0).

An OpenSim user requesting a moment arm calculation will specify a muscle, and choose one of the available angular quantities for that muscle. Currently only a generalized coordinate subset is available for this purpose, so θ will always be one of the q 's in the model. When the angle of interest is actually the sum of several coupled rotations, the coordinate associated with one of them (called the independent coordinate) is scaled so that it reads as the total angle rather than just the angle it controls directly. Coupler constraints are added separately to enforce the desired cooperative motion of the dependent coordinates. The algorithm below does not require this approach, but there must be a way to calculate θ from the q 's and $\dot{\theta}$ from the \dot{q} 's.

Note that a muscle path may cross several independent coordinates, such as a hip and knee angle. When moment arm is calculated for one of those coordinates, the other is held rigid (meaning again that it is seen as coupled, but with a coupling factor of 0). Muscles crossing wrist, ankle,

neck, and spine may be modeled with a single independent coordinate measuring the total angle, while several dependent coordinates are coupled to it.

Ways to calculate moment arm

Starting with the definition, there are a variety of ways to calculate moment arm differing in precision, implementation difficulty, and conceptual difficulty.

Finite differencing

We can calculate $r=dl/d\theta$ directly by finite differencing. That is, we can make a small perturbation $\Delta\theta$, satisfy all position constraints, update geometric calculations, and measure the resulting change Δl . The advantage of this method is that it directly implements the definition, and it is conceptually very simple. However, it has several drawbacks: it produces an approximate answer, and involves linearization difficulties due to the complex path geometry and the need to ensure satisfaction of the nonlinear position constraints. Also, because this is done at the position level it includes only holonomic constraints, and cannot account for nonholonomic constraints such as rolling.

Velocity-level kinematics

An easier and exact computation is available using velocities, since we have

$$r = \frac{dl}{d\theta} = \frac{dl/dt}{d\theta/dt} \equiv \frac{\dot{l}}{\dot{\theta}} \quad (7)$$

That is, if we can calculate $\dot{l}(\dot{\theta})$ then we need only enforce $\dot{\theta} = 1$ (for example), satisfy all velocity constraints, then calculate $r = \dot{l}(1)$. This is probably the best way to calculate moment arm provided the operator $\dot{l}(\dot{\theta})$ is available. Unfortunately, it can be difficult to calculate \dot{l} so we would like to find an alternative.

Partial velocity method

By assumption (1) above, we have $l = l(q)$ so

$$\dot{l} \triangleq \frac{dl}{dt} = \sum_i \frac{\partial l}{\partial q_i} \frac{\partial q_i}{\partial t} = P\dot{q} = PNu \quad (8)$$

with the last equality coming from equation (3). $P(q)$ is a row matrix whose i^{th} entry is the scalar $p_i = \partial l / \partial q_i$. If we can write $u = C\dot{\theta}$ for some coupling matrix $C(q)$ (a column with entries c_i), then from equation (8) we have

$$\dot{l} = PNC\dot{\theta} \quad (9)$$

Then comparing (9) with (7) and noting that transposing a scalar doesn't change it, we have

$$r = PNC = C^T N^T P^T \quad (10)$$

If we had an explicit representation of P , this would be a very nice way to calculate r . However, this would imply that we can calculate $\dot{l}(\dot{q})$ which we're assuming is difficult. Since generalized forces are dual to generalized speeds, we'll look at how to use forces instead of velocities to calculate r .

Generalized force method

Simbody can map body spatial forces F to generalized forces f via an operator that calculates

$$f = J^T F \quad (11)$$

where J is the system Jacobian (partial velocity matrix) that maps generalized speeds to the body spatial velocities they produce. J just collects together the body Jacobians from equation (5).

Assumption (2) tells us how to calculate F from a given muscle tension scalar s , using the muscle's force transmission matrix T . Substituting (2) into (11):

$$f(s) = J^T T s \quad (12)$$

The column matrix $J^T T$ maps tension to generalized force; the dual problem mapping generalized speeds to \dot{l} is then $\dot{l} = (J^T T)^T u$ (proof?). From equation (8) it follows that $J^T T = N^T P^T$. Substituting into equation (10) and using equation (12) gives

$$r = C^T N^T P^T = C^T (J^T T) = C^T f(s) / s \quad (13)$$

This gives us the algorithm we need for calculating moment arm without knowing how to calculate \dot{l} directly:

1. Determine the coupling matrix C for the angular quantity of interest θ (see below)
2. Apply unit tension $s=1$ to the muscle of interest and map to muscle forces $F(s)$ using operator (2)
3. Use the Simbody operator (11) to map muscle forces $F(s)$ to generalized forces $f(s)$ (see below)
4. Use equation (13) to compute $r = C^T f / s$ (see below)

1. Calculating the coupling matrix C

Set $\dot{\theta} = \dot{\theta}_0 = 1$, use Simbody's `project()` operator to find a least squares solution that satisfies the velocity constraints (this will change $\dot{\theta}$ as well). Determine the new value for $\dot{\theta}$, and call it $\dot{\theta}_1$. Now each $u_i = c_i \dot{\theta}_1$, so $c_i = u_i / \dot{\theta}_1$ and we have determined $C = u / \dot{\theta}_1$.

Code example:

```
// Calculate coupling matrix C:

// Assume "mobod" is a mobilized body whose 0th mobility has been scaled
// so that its generalized coordinate is the angle theta.
state.updU() = 0;
mobod.setOneU(state, MobilizerUIndex(0), 1); // thetadot_0 = 1
system.project(state, 1e-10,
    yWeights, cWeights, yErrEst, // dummies; see below
    System::ProjectOptions::VelocityOnly);
// Now calculate C.
const Vector C = state.getU() / mobod.getOneU(state, MobilizerUIndex(0)); // / thetadot_1
state.updU() = 0;

// Note: you can declare these dummies for the project() call above.
const Vector yWeights(state.getNY(), 1);
const Vector cWeights(state.getNMultipliers(), 1);
Vector yErrEst;
```

3. Mapping spatial forces to generalized forces

If you can collect the muscle's generated spatial body forces F into an array with an entry for each body (zero where the muscle does nothing), you can generate the equivalent generalized forces using Simbody's oddly-named method `calcInternalGradientFromSpatial()`.

Code example:

```
// Calculate the joint torques f equivalent to the muscle forces F, method 1:

Vector<SpatialVec> F; // Indexed by MobilizedBodyIndex
muscle.setTension(s);
// ... obtain F from the muscle somehow
Vector f;
matter.calcInternalGradientFromSpatial(state, F, f);
```

An alternative is to let Simbody gather up all the body and generalized forces produced by all force elements, and work with the difference between inactive and activated muscle.

Code example:

```
// Calculate the joint torques f equivalent to the muscle forces F, method 2:

Vector f0, f1, f;
// Start with the muscle off
muscle.setTension(0);
system.realize(Stage::Dynamics);
matter.calcInternalGradientFromSpatial(state,
    system.getRigidBodyForces(state, Stage::Dynamics),
    f0);
f0 += system.getMobilityForces(state, Stage::Dynamics);

// Now turn on the muscle
muscle.setTension(s);
system.realize(Stage::Dynamics);
matter.calcInternalGradientFromSpatial(state,
    system.getRigidBodyForces(state, Stage::Dynamics),
    f1);
f1 += system.getMobilityForces(state, Stage::Dynamics);

// f is the change in generalized forces due to the muscle
f = f1 - f0;
```

4. Calculating the moment arm

With C and f calculated as above, the moment arm calculation is easy:

```
Real momentArm = ~C * f / s;
```

Appendix: How to map generalized forces to torques

Assuming mass properties are available, we can test consistency between moment arm and the resulting dynamics. We can apply a muscle tension s , calculate moment arm r about some angular quantity θ as above, and also calculate generalized accelerations \ddot{u} and constraint multipliers λ using the equations of motion, that is, by calling `realize(Acceleration)` in Simbody. Then given \ddot{u} and λ we would like to determine the torque τ_θ that must have been applied across the rotational mobilities that contribute to θ , and verify that $\tau_\theta = rs$.

Assume that θ is defined as $\theta = \sum \theta_i$. That is, the angle of interest is determined by the sum of the individual angles at several mobilities. Then we can write $\tau_\theta = \sum \tau_{\theta_i}$ where the summation is taken over the same mobilities as appear in the definition of θ . Note that the angles θ_i do not necessarily correspond to generalized coordinates, since OpenSim allows generalized coordinates to be scaled. Similarly, the τ_{θ_i} are not generalized forces since those must be scaled to be consistent with the generalized speeds.

Denote the scaling of the i^{th} generalized speed w_i such that $\dot{\theta}_i = w_i u_i$. Then we must have $\tau_{\theta_i} = f_i / w_i$ because $f_i u_i$ must have physically meaningful units. So now we can use inverse dynamics to calculate $f = M\ddot{u} + G^T \lambda$ and calculate $\tau_\theta = \sum f_i / w_i$ and compare it with rs .

The only remaining question is how to determine the scaling factors w . These come directly from the definition of the generalized speeds for the mobilizer connecting a body B to its parent P :

$${}^P V^B \triangleq \begin{bmatrix} {}^P \omega^B \\ {}^P v^B \end{bmatrix} = {}^P H^B u \quad (14)$$

Dropping superscripts and writing $H = \begin{bmatrix} H_\omega \\ H_v \end{bmatrix}$ shows that $\omega = H_\omega u$, thus $|H_\omega|$ is the scaling

factor that relates u to angular velocity in radian/s. Thus we have $w_i = |H_{\omega,i}|$. Columns of H may be obtained via the `getHCol()` method of `MobilizedBody`:

```
const SpatialVec H_PB_G = mobod.getHCol(state, MobilizerUIndex(0));
Real wi = H_PB_G[0].norm(); // select the angular component, calculate magnitude
```