**Title**

* Calculation of a vector moment arm for human biomechanical analysis
* Human muscle moment arm calculation through use of vectors
* Vector based calculations for moment arms that drive human musculotendon torque

**Hypotheses**

* I hypothesize that calculating musculotendon moment arms through vector analysis will result in a better understanding of the effects of muscles on joint stability than the current scalar calculation of musculotendon moment arms.
* I hypothesize that scalar calculations of moment arms produced by muscles can be improved by use of vector calculations and provide better comparison to physical actuation.
* The use of a vector-based calculation for computing moment arms will provide more useable information about the biomechanics of joint actuation than a scalar quantity based method.
* I hypothesize that by calculating and treating musculotendon moment arms as a vector, the applicability and accuracy of modeling 3D systems will be improved.

**Sentence Outline**

1. Abstract
   1. This paper demonstrates a compact algorithm for calculating musculotendon moment arms as a vector originating from a joint.
   2. Current biomechanical research calculates musculotendon moment arms as a scalar value, which limits its applications.
   3. Results from this method show that it is able to match the previous calculations for the moment arm while at the same time providing more information on how the musculotendon actuators generate moment arms along axes orthogonal to the primary axis of rotation.
   4. This method can be used for more robust information about the torque that muscle generate about joints in 3D models and can have further implications to how muscles synergize with on another to maintain joint stability during motion.
2. Introduction
   1. Humans generate motion by contracting their muscles about a joint in order to actuate their limbs.
      1. By contracting muscles, torque is produced about a joint, and this torque causes motion of the limbs.
   2. The current standard for calculating moment arms for simulation and research is through the use of a scalar formula.
      1. This equation requires two or more joint position for calculation.
      2. It was originally created for the intended goal of being computationally efficient, however this efficiency is negligible with modern computing.
      3. This equation oversimplifies multiple degree of freedom joints, but is sufficient for single degree of freedom revolute joints.
   3. Information on the torque that is produced about a joint is lost when the moment arm is considered to be a scalar quantity.
      1. The moment arm calculated only relates to the moment that is generated about the axis that is being rotated.
      2. Musculotendon actuators are not typically coplanar with the joint’s plane of rotation, meaning that the torque that can be calculated from a scalar quantity does not include the torque that is produced on other direction unrelated to the joint motion.
   4. The scalar quantity moment arm calculation is useful for 2D simplifications for human motion, but struggle at providing accurate information for 3D models.
      1. Moment arm calculations about the hip joint are the most impacted by having a moment arm being a scalar value.
   5. Hypothesis (one from the above section)
      1. The use of this vector moment arm will result in more robust information about the torques that are produced about a joint.
      2. A vector moment arm will also produce better information about how joints are stabilized through the use of muscles that produce moments about axes that are not the rotated one.
3. Methods – Musculotendon Geometry
   1. Muscles can be simplified as straight line actuators with an origin on one bone, an insertion on another bone that is separated by one or more joints from the origin point, and some amount of intermediate points between the two that changes the direction of the muscle.
   2. Joints can be simplified as frictionless revolute pivot points.
      1. Joints need to have a defined number of degrees of freedom.
      2. The knee joint has the additional complication, as the instantaneous center of rotation changes as the knee actuates, but this can be accounted for through the use of kinematic analysis.
4. Methods – Perturbation method
   1. The standard for calculating human moment arms is by calculating the change in length of a muscle due to a change in angle in the joint.
      1. By looking full range of motion of a joint along one axis, the change in muscle length can be calculated through kinematic geometry.
   2. This formula computes a scalar value for the moment arm at any position of the joint.
   3. Multiplying this scalar value by the scalar value of the musculotendon force produces a moment at that position and is assumed to be about the axis of revolution.
5. Methods – Vector moment arm calculation
   1. The following vector moment arm calculations can be done at any point of the joints rotation and does not need to be differentially calculated.
      1. It requires knowing the location for the origin, insertion, and any intermediate points along a simplified musculotendon actuator.
      2. If these points are located in different reference frames, it also requires knowing the relative position between these frames in order to bring all points along the actuator into a common reference frame.
   2. First, all points need to be brought into a common reference frame.
      1. The reference frame that they should be brought into is the frame of the joint of interest.
      2. Points along a muscle can be treated as vectors, which start at the joint reference frame and point to their location.
      3. Moving points into a common reference frame can be done through the use of a transformation matrix, which combines a rotation matrix between two frames and the distance between those frames.
   3. With all points contained within a single reference frame, we can develop a unit vector that describes the direction of the muscle between two specific points.
      1. The two points to use are the ones in which they are assumed to contain the change in muscle length between them.
      2. These two points will typically be the last point along the geometry of a muscle path contained in the first reference frame, and the second point will be the first location in the second reference frame.
      3. If a muscle has no intermediate points that change it’s direction, then the points will be the origin and insertion point.
   4. Multiplying the unit direction by the dot product of the unit direction and the inverse of the second point results in a vector that begins at the second point and points to the location along the muscle path that is orthogonal to the joint.
      1. Adding this vector and the vector that describes the second point creates the moment arm vector that originates at the joint and points orthogonally to the muscle path.
6. Methods – Muscle Model
   1. When calculating the force that is generated by the muscles, the equilibrium musculotendon model is used.
      1. This model assumes that musculotendon actuators are composed of an active contractile component and a passive elastic component that are linked with an elastic tendon.
   2. The force that a muscle is able to generate is computed using an iterative method that determines the length of the tendon that satisfies a force equilibrium equation.
      1. **How in depth should this review cover equilibrium method? Every paper that mentions this method includes the equations and graphs for the components. Might be nice in order to round out this paper, but it has been covered a bunch.**
   3. Before moving onto calculating the torque, the scalar value that describes the force that the muscle can produce is multiplied by the unit direction vector that was found during the moment arm calculation.
      1. By multiplying the force by the unit direction vector, we now have a force that is described as a vector, which is important for the torque calculations.
7. Methods – Torque calculation
   1. To calculate the torque that a muscle produces about a joint, the moment arm vector is crossed with the force vector.
      1. This will generate a torque with x, y, and z components.
      2. Depending on the type of motion that is being generated, the presence of multiple axes of torque means that other muscles will need to activate in specific ways in order to prevent undesired motion from occurring.
8. Results – Vector Moment Arm and OpenSim Comparison
   1. To look at the efficacy of a moment arm calculation through the use of vectors, we can compare results derived from it with results from the perturbation method.
      1. To take a simple case, let’s look at a simplified adductor magnus, which actuates the hip joint through abduction and adduction.
      2. Plot for moment arm during pure adduction
      3. Looking at the moment arm it creates through adduction isn’t the whole story however, as there is also a moment arm that is created that would cause flexion as the muscle contracts.
      4. Plot of moment arm in other directions
      5. The perturbation method also becomes unwieldy when looking at the moment that the muscle can produce when the hip is already flexed some amount.
9. Results – Biarticulate Muscles
   1. This method for calculating moment arms is also useful for identifying the torque that is placed on all joints that a biarticulate muscle crosses over.
   2. In the first case, the muscle segment that changes length and produces actuation crosses over two joints.
      1. The bicep femoris long head muscle falls into this category.
      2. Plot for the bicep femoris moment arm about the hip and about the knee
   3. In the second case, the biarticulate muscle has one muscle segment that actuates the first joint and a different muscle segment that actuates the second joint.
      1. The sartorius muscle is an example of this case.
      2. This case is neglected through the use of the perturbation method, as the muscle segment crossing over the unactuated joint does not change length, but will still have torque produced about it.
      3. Plot for the sartorius moment arm about the hip and about the knee
10. Discussion
    1. We can see that by doing a vector analysis that we get more information about a musculotendon moment arm than other methods for this calculation, while maintaining the accuracy.
    2. The vector method can be difficult to use for muscles that connect to the patella, but this is an area that the perturbation method would also have difficulty in.
11. Conclusion
    1. This paper has demonstrated the use of a vector algorithm for computing human musculotendon moment arms that has more applicability to 3D human biomechanics than the perturbation method.
    2. This method provides more information on the torque that musculotendon actuators produce about joints than previous methods.
       1. This method can be used for joint stability analysis, in which we can now look at how other muscles act in an antagonistic fashion to create smooth motion in one direction and minimizing motion in unwanted directions.
    3. This method also removes the need for finite differencing a muscle’s kinematic geometry in order to calculate a moment arm and allows a biomechanist to calculate the moment arm at any orientation.
    4. One advantage that the perturbation method has over this method is that it is more computationally efficient.
       1. The computational efficiency however is less desirable than more robust information about the moment about a joint.
12. References
    1. Hoy
    2. Delp 1990
    3. Sherman 2013
    4. Hill 1938
    5. Millard 2013
    6. Young
    7. Joint Stability
    8. Joint Stability
    9. Other moment arm calculators
    10. Equilibrium musculotendon papers
    11. Muscle Synergies?

**Notes**

* I think the strongest arguments that I want for this paper are:
  + Accurate 3D information over 2D simplifications
  + Easy to implement for any joint configuration
  + Joint stability and analysis
* Possibility of extending this into a physical system for robotic systems.
  + If trying to publish to a robotics conference, I think there can be an extended results/discussion/conclusion based around the applicability of this in biomimetic robotic systems.
  + Can discuss the stresses that are placed on joints and structures due to torsions from the actuators.
  + The motion from musculotendon actuators aren’t simple bending moments.
* I want data on human moment arms that come from literature, but many of them are from 1992 and prior, which makes accessing them difficult, but likely important for comparison.
  + Can compare also to recorded torque from people