Computational approaches to determine muscle-generated feasible endpoint forces constraining capabilities of human movement

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Introduction: Pseudo-static analysis of mechanical outputs during behavioral tasks such as gait can provide insight into biological operational spaces. The set of all mechanical outputs from a static joint configuration called feasible endpoint force space (FFS) envelopes ground action forces during gait [1], which effectively constrains the capabilities of human movement. To improve treatments and rehabilitations for movement disorders aiming to improve patient capabilities, approaches for both 2D and 3D computations of dynamic, muscle-generated feasible endpoint forces are relatively unexplored. Particularly for use in gait analysis, these approaches may provide necessary bridges between approaches in computational geometry and musculoskeletal modeling to study and design therapies for movement disorders.

Methods: We used OpenSim to compute endpoint forces for the human lower-limb joints during normal gait [2] for a simple 2D 10 DOF musculoskeletal model with 18 muscles and a complex 3D 23 DOF one with 92 muscles. For each frame of gait cycle data, the FFS was determined by the Minkowski sum of the generator vectors, or columns of $\mathbf{w} = \mathbf{J}^{-\mathbf{T}}\,\mathbf{R}\,\mathbf{F}$, where $\mathbf{J}^{-\mathbf{T}}$ is the limb inverse transpose kinematic Jacobian, **R** is the muscle moment arms matrix, and **F** is physiology-informed muscle strength. The 2D FFS was computed by summing generator vectors in order by circular indexing according to their ascending polar angles. The Jarvis algorithm can be used to find the convex hull. The 3D Minkowski sums of nonconvex sets is a more complex problem [3]; consequently, an extension of the 2D approach was used to sum generator vectors in order by circular indexing according to the ascending polar angles of their projection on to a plane normal to a chosen, or seed, generator vector and the process was repeated using each generator vector as the seed.

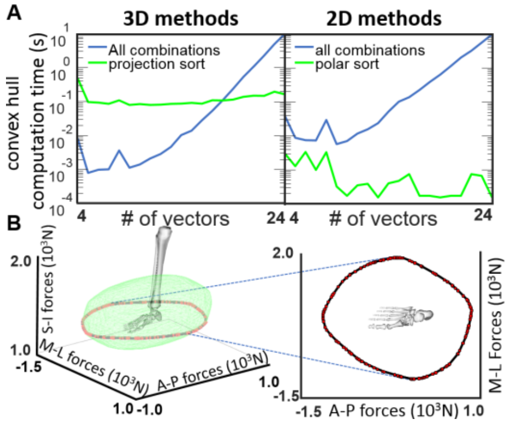

Figure 1: a) log plots of computational time highlighting method efficiency. b) Given a constraint, such as recorded support ground reaction force, we can rapidly investigate the plane slice by finding the orthonormal basis, yielding information about transverse forces during gait and allowing us to reduce computational complexity.

Results and Discussion: The highlighted $\mathbf{R}^2$ and $\mathbf{R}^3$ computational approaches are superior to approaches that require all possible linear combinations of the generator vectors; moreover, the seeding and circular indexing is highly parallelizable (Figure 1).

Conclusions: We found 2D and 3D computational approaches, largely unused in gait analysis, capable of being used with existing musculoskeletal modeling and simulation frameworks to determine endpoint force capabilities of human movement. These approaches may be broadly applied to analyze any serial manipulators (e.g., robot, limb, finger) and investigate other feasible spaces, such as feasible torques or wrenches. Future work will incorporate these approaches into forward dynamic simulations of movement.

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References: [1]: Valero-Cuevas FJ. *Fundamentals of Neuromechanics*, 2016. [2]: Delp SL, et al., *OpenSim: Open-Source Software to Create and Analyze Dynamic Simulations of Movement*, IEEE Trans BME. 55:1940-1950, 2007. [3]: Fogel E. & Halperin D., *Exact and Efficient Construction of Minkowski Sums of Convex Polyhedra with Applications*, ALENEX, 2006.