

Volume Invariant Cosserat Rods for Muscle Deformation

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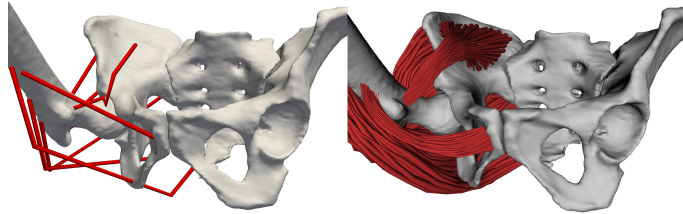


We model muscles as interacting active fibers instead of a deforming surface, obtaining realistic muscle deformation, validated biomechanical behavior, and interactive performance

Motivation

The problem: Personalized musculoskeletal models are digital twins of the human body. They predict how muscles and joints behave during movement, supporting surgical planning, implant design, rehabilitation, and biomechanical research. Before a surgeon replaces a worn hip, the forces the surrounding muscles put on the joint cannot be measured inside a living patient, so the advice the surgeon gets is only as good as the model.

Challenge: To provide reliable predictions, these models must reproduce how muscles actually deform. Flex your arm and the biceps does not merely shorten: it visibly *bulges*, because muscle tissue is almost incompressible, so the length it loses it must gain in width. Fast, interactive methods represent a muscle only as its outer shell [1], or as a line of segments stretched between two bones, missing this internal behavior entirely, while detailed physics-based simulations capture it but are far too slow for practical use. Combining realistic internal deformation with interactive performance therefore remains a major challenge.



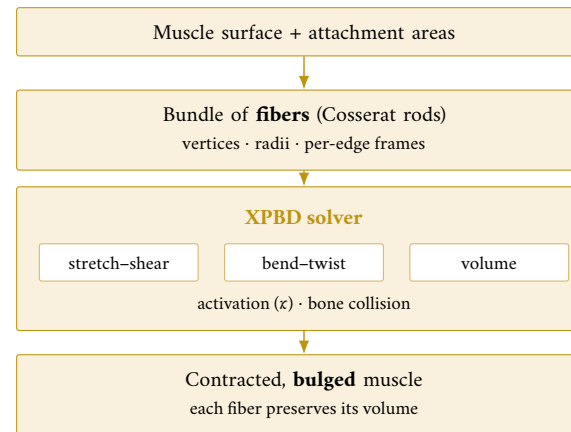
Hip muscles during flexion (bones in grey). Left: how they are represented for force estimation today, as a few straight segments running between fixed points, with no cross-section and no volume. Right: the same muscles as bundles of fascicle rods filling their interiors, each thickening as it shortens.

Our idea

We represent each muscle as a bundle of **fibers**, generated automatically from the muscle's shape and distributed throughout its volume from origin to insertion. Individual fibers contract according to muscle activation while preserving their volume and respecting the surround-

ing bones. Their collective behavior reproduces the overall muscle deformation and realistic muscle bulging.

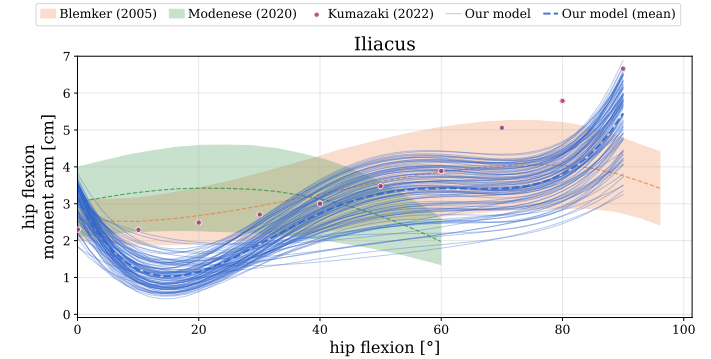
Each fiber stands for a *fascicle*, a bundle of muscle fibers, and is modeled as a **Cosserat rod** [5], a slender structure that bends, twists, stretches, and shears. Following VIPER [4], every vertex carries a *radius* as an additional degree of freedom, and a volume constraint couples that radius to the rod's length, so shortening a rod forces it to thicken. Bone motion and muscle activation drive the rods using **Extended Position-Based Dynamics (XPBD)** [3], a fast and stable technique borrowed from computer graphics.



How the method works. Fibers are generated from the muscle surface and its attachment areas, then modeled as Cosserat rods. The solver enforces three constraints every step, and the volume constraint turns contraction into bulging.

Results and discussion

Four hip muscles (iliacus, gluteus maximus, gluteus medius, adductor brevis) were evaluated during hip flexion and abduction. **Predicted moment arms, a measure of each muscle's leverage on the joint, follow published experimental and computational data [6] across most of the range of motion.**



Iliacus moment arm during hip flexion. Each blue curve is one fiber, the dashed curve their mean. Shaded bands and points show what published studies report (bands: Blemker 2005, Modenese 2020; points: Kumazaki 2022) [6]. The more the blue overlaps them, the closer the model is to the literature.

The approach reaches interactive rates of roughly **26 frames per second** on an ordinary 8-core laptop, so a movement can be explored as it is simulated. This is possible because most of each fiber's constraints are independent of the other fibers, so the bulk of the work is processed in parallel. Built on the existing framework of Červenka (PBD) [1] and Havlíček (XPBD) [2], the method is approximately **24× faster** than the previous surface-based approach while producing more realistic muscle deformation.

Because fascicles are what ultimately generate muscle force, capturing their behavior directly opens the door to more trustworthy surgical planning, better-fitting implants, and richer inputs for musculoskeletal analysis.

Key references: [1] Kohout & Červenka, *Muscle Deformation Using Position Based Dynamics*, Springer, 2021. [2] Havlíček, *Muscle interaction in the context of muscle deformation modelling by a PBD method*, Master's thesis, UWB, 2024. [3] Macklin et al., *XPBD*, MIG 2016. [4] Angles et al., *VIPER: Volume Invariant Position-based Elastic Rods*, 2019. [5] Kugelstadt & Schömer, *Position and Orientation Based Cosserat Rods*, SCA 2016. [6] Blemker & Delp 2005; Modenese et al. 2020; Kumazaki et al. 2022 (validation data).