

Predictive Simulations of the Upper Limb Using a Closed-Loop Kinematic Shoulder Model

Benjamin Moreno, Valentin Sonnevile, Cédric Schwartz, Olivier Brûls

Aerospace and Mechanical Engineering Department
University of Liège
Allée de la Découverte 9, 4000 Liège, Belgium
(b.moreno, valentin.sonneville, cedric.schwartz, o.bruls)@uliege.be

1 Introduction

Predictive optimal control simulations of the upper limb offer a powerful framework for optimizing the design of assistive shoulder exoskeletons and anticipating post-operative biomechanical adaptations, such as those following tendon transfers or Reverse Total Shoulder Arthroplasty (RTSA). Nonetheless, their widespread adoption has been limited until now because of their high computational cost and the challenges associated with numerical convergence [2], [4]. Such simulations have been applied to the upper limb, typically using models that approximate the shoulder girdle by coupling the scapula kinematics to humeral angles via regression equations, enforcing a predefined shoulder rhythm [4]. However, such models fail to capture scapular kinematics when deviations from the prescribed rhythm occur and do not accurately predict the contribution of thoracoscapular muscles to shoulder motion [6]. Several detailed shoulder models, including those by [6] and [7], introduce a closed kinematic loop within the shoulder complex. While these models demonstrate high accuracy for inverse kinematics and dynamics, where the motion trajectory is prescribed, their application in predictive optimal control simulations remains computationally challenging. A primary obstacle is that most state-of-the-art biomechanical optimal control solvers rely on a recursive coordinate formulation, where handling the differential-algebraic equations (DAEs) inherent to complex closed kinematic loops significantly increases computational cost and complicates numerical convergence [3].

2 Methodology

We propose to use a detailed shoulder model that contains a kinematic closed-loop for predictive optimal control problems, using a framework well-suited for constrained mechanical systems available within the Odin software [1]. Odin is a multibody software based on the Lie group formalism on $SE(3)$ and an implicit integration scheme, allowing for the robust handling of DAEs. Biomechanical functionalities, including muscle elements, appropriate joint elements and a shooting-based optimal control framework, have been integrated to enable the efficient predictive simulation of musculoskeletal systems characterized by closed kinematic loops. Notably, the sensitivities for each element of the system are determined analytically, and the gradients for the optimal control problem are computed using a discrete adjoint method. This formulation yields exact gradients and ensures high computational efficiency and robust convergence. Despite the rich representation of the system, which involves a larger set of coordinates, preliminary results indicate that our framework achieves computational performance competitive with other state-of-the-art biomechanics solvers, which typically rely on finite differences for computing the gradients. This efficiency is particularly notable as kinematic complexity increases, such as when introducing closed kinematic loops.

The musculoskeletal model employed in this study is adapted from the upper limb model described in [6] and is depicted in Fig. 1. The shoulder girdle consists of a sternoclavicular joint (modeled as a universal joint), acromioclavicular and glenohumeral joints (modeled as spherical joints), and a scapulothoracic joint that closes the kinematic loop by constraining the scapula to glide over the thorax with 4 degrees of freedom. The model comprises 33 Hill-type muscles. Wrapping surfaces are omitted, the focus of this study being the predictive optimal control framework.

3 Case Study

To evaluate the predictive capabilities of the framework, we define two functional tasks similar to those performed in [6] for inverse dynamics. First, we simulate shoulder flexion by prescribing the initial pose and the final glenohumeral elevation, allowing the optimizer to resolve the required muscle excitations and scapular kinematics. These results are compared against a regression-based model (MoBL-ARMS [5]) to verify the emergence of a physiological shoulder rhythm. Second, we simulate shoulder



Figure 1: Musculoskeletal model of the upper limb adapted from [6], featuring a closed-loop kinematic formulation of the shoulder girdle.

shrugging by constraining the final clavicle elevation. This task highlights the advantages of the representation of the closed kinematic loop, as such independent scapular control cannot be reproduced by models relying on regression-based scapular coupling.

4 Conclusion

These examples demonstrate the feasibility of simulating the shoulder girdle with detailed closed-loop kinematics within a predictive framework. The first objective of this study is to establish the computational viability of the proposed numerical method for such complex topological systems. Although the framework successfully generates predictive solutions, capturing the physiological fidelity required for practical applications necessitates further model refinements, including the adjustment of muscle lines of action and subject-specific tuning. Nonetheless, the ability to handle such topological complexity is a critical step toward advanced biomechanical applications for the upper limb. This framework paves the way for future work in pre-operative planning and the design of exoskeletons, where a deep understanding of the shoulder girdle is essential.

Acknowledgments: This research benefits from the AidWear project, generously funded by FOD BOSA.

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