The Effect of Kinematic and Dynamic Redundancy on the Assessment of Joint Reaction Loads

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1. Introduction

The human musculoskeletal system has a redundant structure, i.e. there are more Degrees of Freedom (DoFs) than those required to perform a certain task (kinematic redundancy) and each DoF is actuated by multiple muscles (dynamic redundancy). Unfortunately, most musculoskeletal models have a lower dimensionality than the actual system they are simulating. This simplification is deliberate, since it also simplifies the mathematical implementation and analysis, but negatively affects the validity of these models and the obtained results. We employed well-established techniques from linear algebra and projection operators to extend the underlying kinematic and dynamic relations by modeling the redundancy effects in null space. The usefulness of the proposed framework is demonstrated in the context of estimating the bounds of the joint reaction loads for a gait movement, where we show that misinterpretation of the results is possible if the null space forces are ignored. The proposed framework rigorously accounts for the effects of kinematic and dynamic redundancy leading to a complete description of the system.

2. Materials and Methods

It has been shown that task-based projection can be used effectively for planning and simulation of constrained musculoskeletal systems [1] and furthermore, it provides the means to identify the kinematically redundant DoFs. In a similar vein, the dynamic redundancy effect can be exploited by defining the kinematic and dynamic relations among the muscle and joint space quantities (e.g. muscle length and joint coordinates and muscle forces and joint forces) using the muscle moment arm ($\boldsymbol{R}$) and extend the underlying equations of motion. Here we will concentrate only on the force relationship

$$\boldsymbol{\tau} = -\boldsymbol{R}^T \boldsymbol{f}_m, \boldsymbol{f}_m = -\boldsymbol{R}^{+T}\boldsymbol{\tau} + \boldsymbol{N}_{\boldsymbol{R}}^T \boldsymbol{f}_{m0} \qquad (1)$$

where $\boldsymbol{\tau}$ are the joint space generalized forces and $\boldsymbol{f}_m$ are the muscle forces. Note that when mapping from a high-dimensional subspace, in this case from muscle space to joint space, then the problem is straightforward, however, the inverse mapping is not unique and requires the introduction of the null space contribution ($\boldsymbol{N}_{\boldsymbol{R}}^T \boldsymbol{f}_{m0}$), where $\boldsymbol{f}_{m0}$ can be arbitrary selected. The benefits of this formulation are shown by the fact that for a given action, the feasible muscle forces $\boldsymbol{f}_{\boldsymbol{m}}^{\oplus}$ can be determined by identifying the null space forces $\boldsymbol{f}_{m0}$, which satisfy both the action and the physiological muscle constraints

$$\boldsymbol{Z}\boldsymbol{f}_{m0} \preccurlyeq \mathbf{b}, \boldsymbol{f}_{\boldsymbol{m}}^{\oplus} = \left\{-\boldsymbol{R}^{+T}\boldsymbol{\tau} + \boldsymbol{N}_{\boldsymbol{R}}^T \boldsymbol{f}_{m0,i}, \forall i\right\}. \qquad (2)$$

3. Results

The usefulness of evaluating the feasible muscle forces is demonstrated in the context of joint reaction analysis on a gait movement (Fig. 1). An accurate estimation of the muscle forces is critical for the assessment of joint reaction loads. Therefore, the null space contributions can significantly alter the reaction forces without affecting the movement.

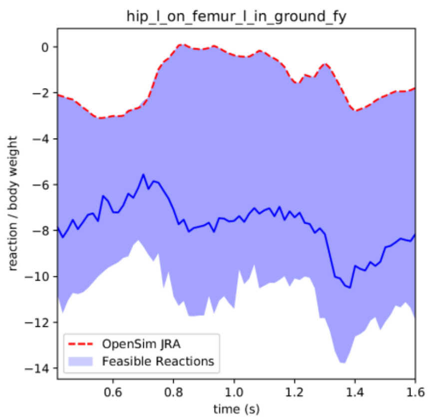

Fig 1 The normalized vertical reaction load on the hip joint for a single gait cycle. The shaded area is the feasible reaction force as attributed to the null space solutions of muscle forces. The red dotted line are the results obtained from OpenSim.

5. References

1. D. Stanev and K. Moustakas, "Simulation of Constrained Musculoskeletal Systems in Task Space," IEEE Trans. Biomed. Eng., vol. 65, no. 2, pp. 307–318, 2018.

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