Simulation of maximum isometric and isokinetic elbow actuation torques based on zonotopes

Jonathan Savin, Diane Haering, Nasser Rezzoug, Charles Pontonnier

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J. Savin[a*], D. Haering[b], N. Rezzoug[c] and C. Pontonnier[b]

[a] *INRS, Vandoeuvre-lès-Nancy, France;*
[b] *ENS/INRIA/IRISA/M2S MimeTIC, Rennes, France;*
[c] *PPrime Institute, CNRS-University of Poitiers-ENSMA, UPR 3346, France*

1. Introduction

How can work equipment designers estimate the maximum joint actuation torques that operators can perform at the workstation? These data are essential for ergonomic risk assessment, yet designers usually only have at their disposal the databases provided with digital mannequin software. These are often approximate (Hall et al. 2021), leading to potential under-estimation of occupational risk exposure. This study describes a methodology based on zonotopes and musculoskeletal simulation to provide designers with more comprehensive and more reliable estimates of maximum actuation torques. As a partial validation process, this study also compares such simulated maximum actuation torques to experimental data described in the literature (Frey Law et al. 2012; Haering et al. 2019) focusing on maximum isometric and isokinetic actuation torques of the elbow.

2. Methods

2.1 Mathematical and modelling approach

The upper limb is described as a musculoskeletal system made of m muscles and p rigid bodies linked together by N degrees of freedom (DoF). Let $\boldsymbol{R} = [r_{i,j}]$ be the matrix of the moment arms of muscle j relative to the DoF i. $\boldsymbol{R}$ depends only on the joint angles $\boldsymbol{q}$ of the system. Let $\boldsymbol{t}$ be the vector of individual muscle tensions. Considering a Hill-type muscle model accounting for the active/passive length/velocity force relationships, $\boldsymbol{t}$ depends on joint the angles and velocities $(\boldsymbol{q}, \dot{\boldsymbol{q}})$. Hence the vector $\boldsymbol{\tau}$ of actuation torques is:

$$\boldsymbol{\tau} = \boldsymbol{R}(\boldsymbol{q})\boldsymbol{t}(\boldsymbol{q}, \dot{\boldsymbol{q}}) \qquad (1)$$

The set $\boldsymbol{T}$ of all achievable muscle tensions is a hypercube of dimension m. In this study, its bounds have been computed using OpenSim (Seth et al. 2018) and the musculoskeletal model of the upper limb “MOBL” described in (Saul et al. 2015). This model represents a male subject with a height of 1.77 m and a mass of 75 kg. It includes 50 muscles and 7 DoFs.

According to equation (1), the set of achievable actuation torques is the image of $\boldsymbol{T}$ through the linear mapping defined by $\boldsymbol{R}$. This set, denoted **Z,** is a special type of convex polytope called a zonotope, which can be computed using the hyper-plane shifting method (Gouttefarde and Krut 2010). Any point on the external surface of $\boldsymbol{Z}$ is an extremum, where at least one joint torque is maximum. Hence, computing maximum joint actuation torques is equivalent to computing intersections or projections of $\boldsymbol{Z}$ with a line or a surface in the space of actuation torques.

2.2 Comparison with experimental data

As a partial validation process, we conducted simulations for two experiments, on the one hand that of (Frey Law et al. 2012), hereafter denoted *FL*, and on the other hand that of (Haering et al. 2019), hereafter denoted *H*. Both concern the joint torque-velocity-angle relationships (JTVAR) of elbow flexion and extension. The first focuses on concentric exertion, the latter addresses eccentric exertion in addition.

3. Result and discussion

3.1 FL-experiment

We used the experimental data corresponding to 30 male subjects (mean height of 1.80 m and mass of 81.5 kg). Figure 1 compares the experimental and simulated maximum actuation torques. The Root Mean Square (RMS) difference in normalized actuation torque is about 27% and 20% for flexion and extension exertion respectively.

3.2 H-experiment

This experiment involved 34 subjects, but we only considered the subject whose height and mass were the most similar to the MOBL model. Figure 2 shows the experimental and simulated normalised maximum flexion and extension joint torques depending on joint velocity. The RMS is about 7% and 16% for flexion and extension exertions.

3.3. Discussion

Simulated and experimental torques show similar trends. This may be a significative benefit of this approach over DHM data that completely neglects the influence of joint velocities on actuation capabilities. However a normalisation processing is needed because the MOBL model is not parameterised according to subjects’ anthropometry and performance.

4. Conclusion

This paper describes a method to estimate joint actuation performance based on zonotopes and musculosketal simulation. This approach can be used to simulate complex experiments, including isokinetic exertions. As a first validation step, this study shows that such simulations account for the global trends observed experimentally, even without any customization of the musculoskeletal model. This parameterisation step is to be explored further to reduce the gap observed between experiments and simulation. Scaling the model anthropometry, the individual muscle capacities and moment arms should be the main levers to play with. If this step is completed, this approach may provide a convenient way to provide work equipment designers with more accurate and comprehensive estimations of maximum actuation performances of operators at the workplace than those at their disposal through current Digital Human Model software tools.

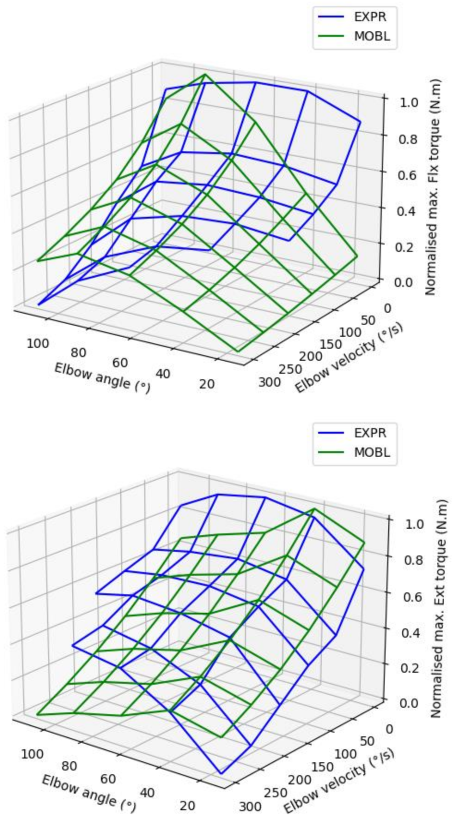

Figure 1: experimental (blue) and simulated (green) normalised maximum flexion (top) and extension (bottom) actuation torques for the FL-experiment.

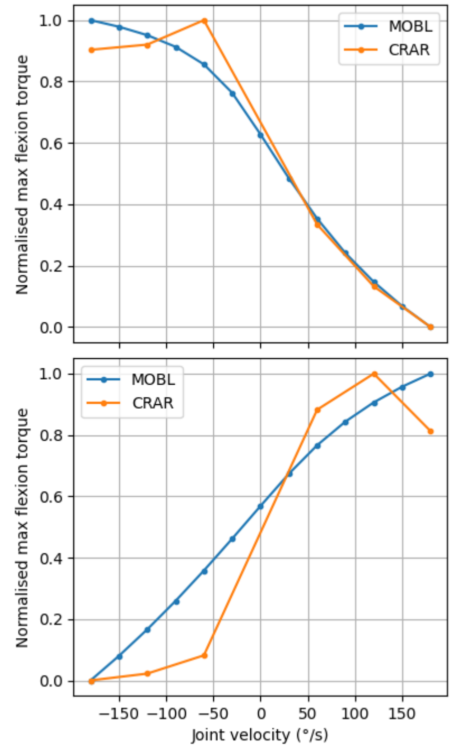

Figure 2: experimental (orange) and simulated (blue) normalised maximum joint torques for one subject of the H-experiment

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***Corresponding author: jonathan.savin@inrs.fr**