SIMULATION OF MAXIMUM ELBOW FLEXION, EXTENSION, PRONATION AND SUPINATION ACTUATION TORQUES BASED ON ZONOTOPES

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Introduction

Maximum joint actuation torques that operators can perform are essential parameters for biomechanical risk assessment at the workplace. However, work equipment designers generally only have access to this data through the databases provided with digital mannequin software such as Delmia Human, Tecnomatix Jack or 3DSSPP. Moreover, these databases are often approximate [1–3] and sparse, leading to potential under-estimation of occupational risk exposure. In this study, a methodology was developed based on *polytopes* [4, 5] and musculoskeletal simulation to provide designers with more comprehensive and more reliable estimates of maximum actuation torques. As a partial validation process, this study compared max torques simulated with our tool to experimental measures described in the literature [6]. This experiment focuses on isometric actuation of the upper limb for different postures of the shoulder, elbow and fore-arm.

Method

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 on the posture of the system. The vector $\boldsymbol{\tau}$ of actuation torques is linked to the vector of muscle tensions $\boldsymbol{t}$ by the equation

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

The set $\boldsymbol{T}$ of all achievable muscle tensions is a hypercube of dimension m. Its bounds can be computed thanks to a musculoskeletal engine (in this study, we used OpenSim [7]). According to equation (1), the set of achievable actuation torques is the image of $\boldsymbol{T}$ through the linear mapping defined by $\boldsymbol{R}$. Linear algebra states that it's a special type of polytope called a *zonotope*, denoted $\boldsymbol{Z}$. The algorithm described in [8] was implemented to compute it efficiently. 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.

Results

The experiment described in [6] was simulated. The maximum isometric elbow flexion, extension, pronation and supination actuation torques were computed for various postures of the upper limb (shoulder, elbow and fore-arm). For instance, figure (1) shows the 3D-surface of maximum elbow flexion torques. Our simulations show similar trends as observed experimentally [6]. For example, maximum flexion torques show an ascending-descending curve with a peak at an elbow flexion angle about 90°; regarding max extension torques, no significant difference was found between neutral and pronated forearm postures.

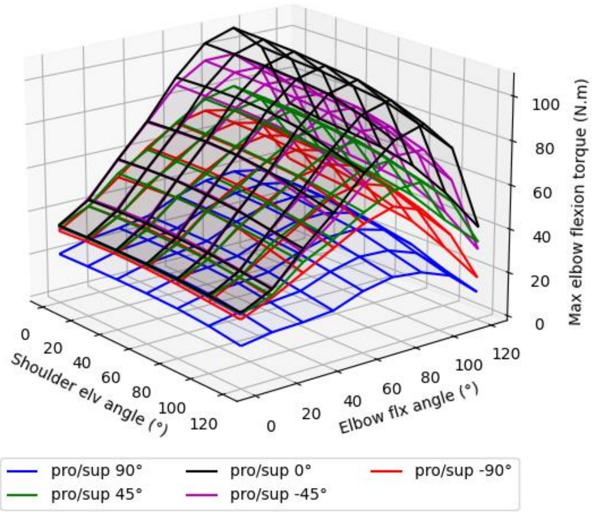

Figure 1: simulated maximum elbow flexion torques for various position of the shoulder, elbow and fore-arm.

Discussion

Considering these experimental and simulated isometric exertions, combining musculoskeletal simulation and zonotope formalism may lead to efficient computations and representations of the complex relations between coupled maximum joint actuations and postures. The validation process should be continued to confirm those encouraging results for non isometric tasks as well. This approach would be a convenient way to provide work equipment designers with more accurate and comprehensive estimations of maximum actuation performances of operators at the workplace.

References

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