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Benchmark of the upper limb in 3D to analyze internal effort quantification and realistic movement reproduction

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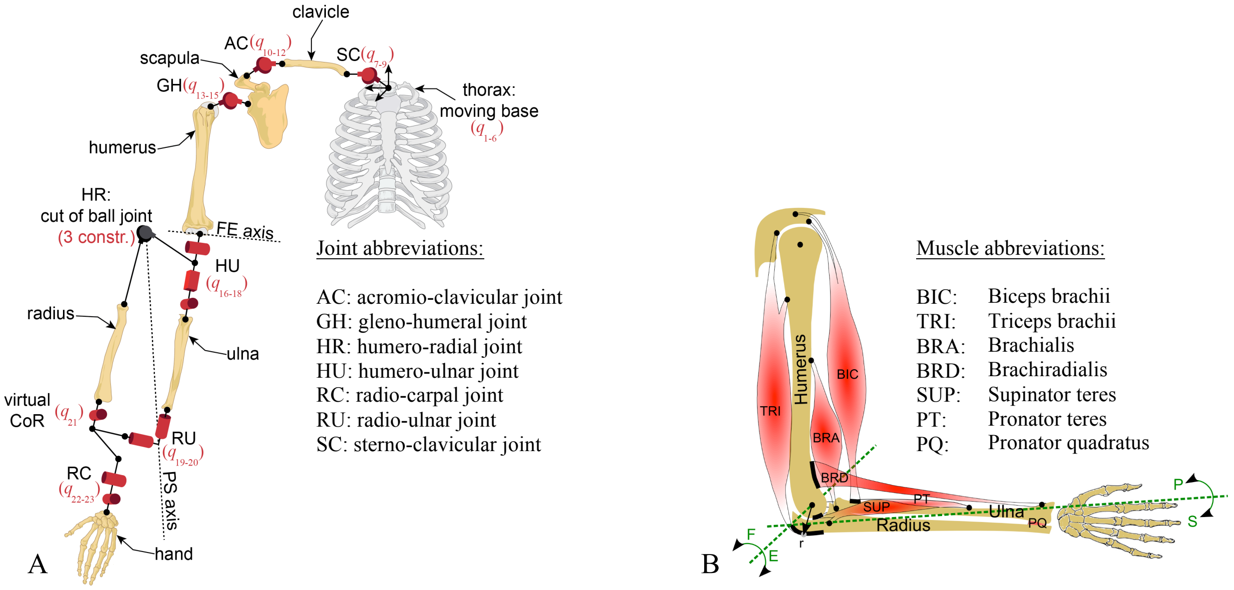
Abstract

Introduction: A realistic dynamic modeling of the upper limb is important for many emerging applications: First, an accurate, reproducible, and fast quantification of joint torques using inverse dynamics is necessary for the personalized design and command of exo-skeletons [1], to evaluate in real-time the torque levels that these ones apply to the human joints. Secondly, the quantification of muscle forces, generally requiring an optimization process attempting to solve the problem of muscle actuation redundancy [2], is necessary to understand the strategies of muscular force distributions, and therefore to develop indicators of muscular functional evaluation for clinical and sports applications, hopefully in real-time in the future. Conversely, the truest possible real-time reproduction of the upper limb movement using direct dynamic models is necessary for the development of realistic bionic arms, myoelectric prostheses, and future tele-surgery robots.

In this context, a benchmark of the upper limb in three dimensions (3D) would be useful to compare and analyze different inverse models to quantify internal efforts, i.e. joint torques and muscle forces, and inversely to check the realistic reproduction of movements using direct dynamic models. The aim of this abstract is to propose a benchmark of the upper limb in 3D to enable comparative analyses of models and methods for the internal effort quantification and realistic movement reproduction.

Methods: The proposed benchmark of the upper limb (Figure 1) considers:

- In Figure 1A, the osteo-articular system, i.e. the bone-joint system, including a refined closed-loop kinematic chain at the forearm, as proposed by [3], and using subject-specific definitions of centers and axes of rotation using functional methods [1].
- In Figure 1B, the musculo-skeletal system, i.e. the osteo-articular system from Figure 1A into which are inserted the seven main muscles actuating the elbow during flexion/extension (FE) and pronation/supination (PS), responsible for the main movements of the elbow and wrist.



Joint abbreviations:

AC:	acromio-clavicular joint
GH:	gleno-humeral joint
HR:	humero-radial joint
HU:	humero-ulnar joint
RC:	radio-carpal joint
RU:	radio-ulnar joint
SC:	sterno-clavicular joint

Muscle abbreviations:

BIC:	Biceps brachii
TRI:	Triceps brachii
BRA:	Brachialis
BRD:	Brachiradialis
SUP:	Supinator teres
PT:	Pronator teres
PQ:	Pronator quadratus

Figure 1: Proposed benchmark, considering A. the osteo-articular system (from [1]), and B. the musculo-skeletal system including the main muscles acting in elbow FE and PS. Revolute, prismatic, and cut of ball joints are resp. represented by cylinders, rectangular prisms, and spheres. The degrees of freedom (dof) are represented by q_i, where index i indicates the dof position in the kinematic chain.

Fifteen healthy subjects performed cycles of elbow FE and PS. The analyzed variables were:

(i) *Joint torques:* obtained from successive inverse kinematics and inverse dynamics processes. The symbolic recursive Newton-Euler equations were generated using ROBOTRAN [4].

(ii) *Muscle forces:* evaluated using an electromyographic (EMG)-driven method [2] based on the maximal isometric muscle force, $F_{max,i}$, the muscle activation dynamics, $a_i(t)$, obtained from the EMG envelope, the muscle force-length $\widetilde{F_l^{CE}}\left(\widetilde{l_{m,i}}\right)$ and force-velocity $\widetilde{F_v^{CE}}\left(\widetilde{v_{m,i}}\right)$ relationships, reminded in Equation 1: $F_{m,i}(t) = F_{max,i} \cdot \left[a_i(t) \cdot \widetilde{F_l^{CE}}\left(\widetilde{l_{m,i}}\right) \cdot \widetilde{F_v^{CE}}\left(\widetilde{v_{m,i}}\right)\right]$. (1)

At each instant *t* of the movement, Equation 2, representing the constraint of muscle redundancy and formulated using the principle of potential powers, is strictly followed to guarantee that the sum of muscle forces $F_{m,i}(t)$ times the muscle tendon potential velocities $\Delta v_i(t), \forall i = 1,\ldots, n$ muscles, are equal to the torque at the joint *J* actuated by these muscles multiplied by the joint potential angular velocity $\Delta\omega_J(t)$ [2].

$$\sum_{i=1}^{n} F_{m,i}(t) \cdot \Delta v_i(t) = M_J(t) \cdot \Delta\omega_J(t) \tag{2}$$

(iii) *Global kinematic reconstruction error:* error between the experimental and the model Cartesian coordinates obtained from direct dynamics, averaged for all markers placed on the upper limb [1].

(iv) *Computation times:* corresponding to the above processes quantifying joint and muscle efforts.

Results: Using the proposed benchmark in 15 healthy adults, illustrative average results of joint torques, muscles forces and global kinematic reconstruction errors are presented in Figure 2. In average, the joint torque samples were obtained in 15 ms and the muscle force samples were obtained in 40 ms. Complementary computational results will be presented at the Conference.

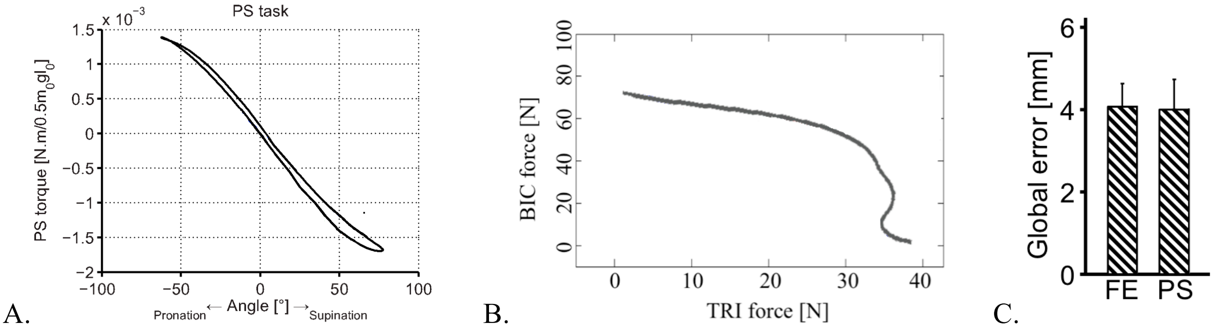


Figure 2: A. Normalized torque-angle pattern during PS. B. Muscle biceps (BIC) and triceps (BIC) brachii forces during FE. C. Global kinematic reconstruction error during FE and PS.

Discussion and conclusion: This benchmark has shown the relevance of the forearm closed-loop kinematic chain to the upper limb model and the personalization of joint centers and axes of rotation, providing larger joint angles and torques (Figure 2A) and leading to a clear decrease in kinematic reconstruction errors (Figure 2C) when compared to models with forearm open-loop kinematic chain [1]. This benchmark has also shown the relevance of using an EMG-driven method to obtain muscle forces (Figure 2B) that respect the constraint of muscle redundancy represented by Equation (2) [2].

The potential of this benchmark consists in the comparison of models and methods for the upper limb functional assessment during unconstrained movements or interactions with haptic devices, and for more realistic design and command of bionic arms, myoelectric prostheses, and tele-surgery robots.

References

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