Upper Limbs Musculoskeletal OpenSim Model: Customization and Assessment

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forces) [3]. In some cases, the computational approach reveals to be complementary to experimental tests to analyze human movements more thoroughly. Generally, numerical simulation presents advantages in terms of cost and time. Several simulation software have been adopted to perform numerical analysis of biomechanical applications [4–7]. Among them, OpenSim is an open-source platform largely used by biomechanical researchers to model musculoskeletal systems.

Considering the spreading of upper limb exoskeletons in the manufacturing field to assist workers [8, 9], it would be beneficial to evaluate their effectiveness in terms of biomechanical load by means of a musculoskeletal model in simulating different working conditions. In OpenSim [10], models with one upper limb are already available. However, to properly simulate human interaction with an assistance robotic wearable device, a new upper limbs model should be developed. Moreover, a customization of the model with anthropometry and muscles properties of single worker would allow evaluating subject-specific conditions.

Therefore, the aims of the research were the development of an OpenSim model with both upper arms and the customization of muscle parameters by subject-specific measures. In this paper, preliminary results of the model assessment were obtained by the comparison of simulated and experimental muscles activation during isometric tests performed by one subject.

2 OpenSim

Several tools [11] are available in OpenSim to evaluate kinematic, dynamic and biomechanical variables. Moreover, the platform provides algorithms based on different optimization-strategies for the estimation of muscle activation.

2.1 Existing upper-limb models

OpenSim models are composed of rigid bodies, joints, wrap objects, muscles and, if present, external forces. For the purpose of the current work, two existing models of upper limb were considered: Arm26 and Standford VA Upper Limb Model [10].

Arm26. right upper limb with 2 degrees of freedom (DOFs) and 6 muscles [10]. It is composed of two rigid bodies: humerus and radius-ulna-hand complex, articulated by a custom joint to allow shoulder elevation movements and elbow flexion-extension. Six muscles are present: Triceps long head, Triceps lateral head, Triceps medial head, Biceps long head, Biceps short head, and Brachialis. The muscles parameters are modeled according to Thelen [12] and properties are based on cadaveric studies.

Standford VA Upper Limb Model. right upper limb with 9 rigid bodies: humerus, radius, ulna, and hand bones. The model depicts a total of 15 DOFs and 50 muscles.

3 Development of an upper limbs model

The upper limbs model developed in this research was based on the previously described models (Arm26 and Standford VA Upper Limb Model) [10] and the full-body model ULB_Project (an extended study of the Standford VA model) [13]. The current developed model is reported in Fig. 1. Considering both left and right upper limbs, model features were:

- 13 rigid bodies: thorax and scapula, clavicle, humerus, radius, ulna, hand;
- 6 DOFs: shoulder flexion-extension and elbow flexion-extension in the sagittal plane, elbow prono-supination in the transverse plane;
- 14 muscles: Triceps long head, Triceps lateral head, Triceps medial head, Biceps long head, Biceps short head, Brachialis, and Brachioradialis;
- 10 wrap objects for the characterization of muscles insertion to the rigid bodies.

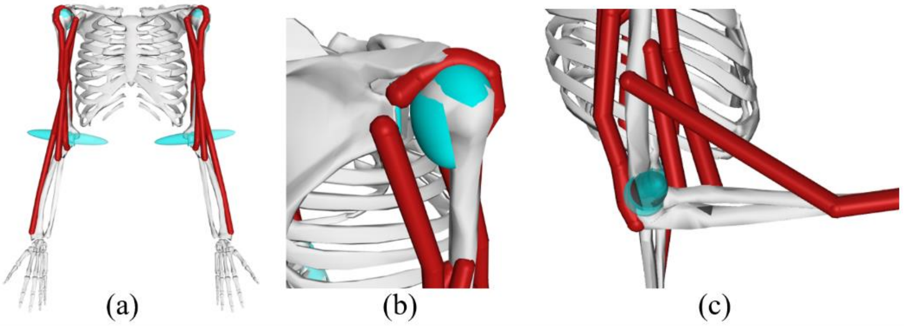

Fig. 1. Two-upper limbs musculoskeletal model: (a) model with rigid bodies (gray), muscles (red) and wrap objects (light blue), (b) the right shoulder, (c) the right elbow.

Bodies. The Bodies represent the rigid elements of the model (Fig 1). Body properties (mass, center of mass position, and inertia tensor) should be defined. The coordinates of the center of mass are with respect to the local reference system, while inertia tensor is expressed with respect to the center of mass.

Joints. OpenSim provides different types of joints: hinge, spherical, prismatic and weld joints. Besides, a custom joint with up to 3 rotations and 3 translations is also available. In the current model weld and custom joints were used. Weld joints linked thorax and scapulas, thorax and clavicles and carpal and metacarpal bones of the hand. Location and orientation of these weld joints were set as in the Stanford VA model. Custom joints connected: (i) thorax and humerus for flexion-extension movement of the shoulder, allowing a range of motion between -90° and 180° (negative values for extension movements); (ii) humerus and ulna for flexion-extension of the elbow, with a range of motion between 0° (extended elbow) and 130°; (iii) ulna and radio for prono-supination of the forearm, with range of motion between -90° (forearm supination) and 90° (forearm pronation). For the left upper limb, the same joints were implemented modifying location coordinates sign and rotations directions according to the reference systems.

Wrap objects. The wrap objects are virtual geometric surfaces fixed on a body (Fig 1). They define muscles insertion on the body and muscles constraints during motion. For each wrap object it must be defined the type (ellipsoid, cylinder, sphere, or toroid), the dimensions, the attachment point and orientation with respect the body they are fixed with. In the presented model, cylindrical wrap objects were added to thorax, in correspondence of the origins of the supraglenoid tubercles of the scapula (Fig. 1b). They were used to wrap Triceps long heads. Ellipsoidal wrap objects were added to the head of the humerus, one anterior and one posterior (Fig. 1b). The anterior ellipsoidal wrap object was used for the Biceps long head, whereas the posterior ellipsoidal wrap object was used for the Triceps long head. Cylindrical wrap objects were added to the humerus in correspondence of the elbow joint (Fig. 1c) to wrap posteriorly Triceps long head, Triceps lateral head, Triceps medial head. Ellipsoidal wrap objects were added to the humerus in correspondence of the elbow joint (Fig. 1c), to wrap anteriorly the Brachioradialis.

Muscles. Muscles type, properties and geometry path should be defined in the model. In this study, Thelen2003 Muscle model type [12] was used for all muscles. In OpenSim model, standardized muscle properties are proposed, based on averaged measurements derived from cadavers.

Model customization. The length, masses, and inertial properties of the 13 rigid bodies of the model can be scaled by using the subject's anthropometry. Muscular properties such as origin and insertion points, optimal fiber length, tendon slack length, pennation angle at optimal fiber length, and maximal isometric force of the model can be customized by using experimental measures.

4 Upper limbs musculoskeletal model assessment

To assess the subject-specific customized model, a male subject (age=24 years, height=179 cm, body mass=79.5 kg) performed isometric tests with different loads. Muscles activity was recorded using superficial electromyography (sEMG). Isometric tests were chosen in this preliminary study to minimize relative movement between muscles and electrodes on the skin.

4.1 Experimental measurement

Muscles characteristic parameters of the subject were experimentally assessed using ultrasounds technology (Echo Blaster 128 CEXT, TELEMED Medical Systems). Since the process was time consuming, only the muscles of the right arm were characterized.

Muscle level of activation was recorded using DuePro (OT Bioelettronica). A couple of bipolar electrodes was placed on the muscle belly by an expert operator according to SENIAM recommendation [14]. Muscle activity was recorded for 3 superficial flexors (Biceps long head, Biceps short head, Brachioradialis, Fig. 2b) and 2 superficial extensors (Triceps long head and Triceps lateral head, Fig. 2a) of the right arm. Deep muscles (Triceps medial head and Brachialis) were excluded because of the difficulties related to collect their activation with sEMG. Elbow angle was collected using the double axes electrogoniometer SG110 (Biometrics Ltd) as in Fig. 2a).

The subject seated on a chair with the armpit against the backrest and the limb beyond the backrest (Fig. 2c). The sEMG signal quality was verified with contractions at different elbow angles. A pre-test was conducted executing maximal voluntary contractions (MVC) with an elbow flexion of 60°. Three isometric tests at elbow flexion 50°, 76° and 108° were performed for five seconds. Each test was repeated without load and holding a dumbbell of 2 kg and 4 kg. The recorded sEMG signals were normalized using muscle level of activation recorded during the MVC. sEMG signals were filtered with a passband filter (Chebyshev, 20-400 Hz) and the normalized root mean square (RMS) was calculated, obtaining muscles activation between 0 and 1.

Fig. 2. Measurements setup: (a) electrogoniometer and sEMG electrodes on Triceps lateral head (TLH), Biceps long head (BLH), Brachioradialis (BRD); (b) sEMG electrodes on BLH, Biceps short head (BSH) and BRD; (c) subject position for tests.

4.2 Simulations

In order to customised the musculoskeletal model upper limb mass equal to 3.98 kg was calculated using the subject's total mass and the percent distribution reported by Winter [15]. Then OpenSim estimated the mass of each body: humerus=2.13 kg, radius=0.62 kg and ulna=0.62 kg. Bodies were scaled according to the subjects' arms (350 mm) and forearms (290 mm) lengths. Muscular properties were customised on the base of data measured by means of ultrasounds. The isometric tests were reproduced in the OpenSim simulations using the kinematic signals collected experimentally (Fig. 3).

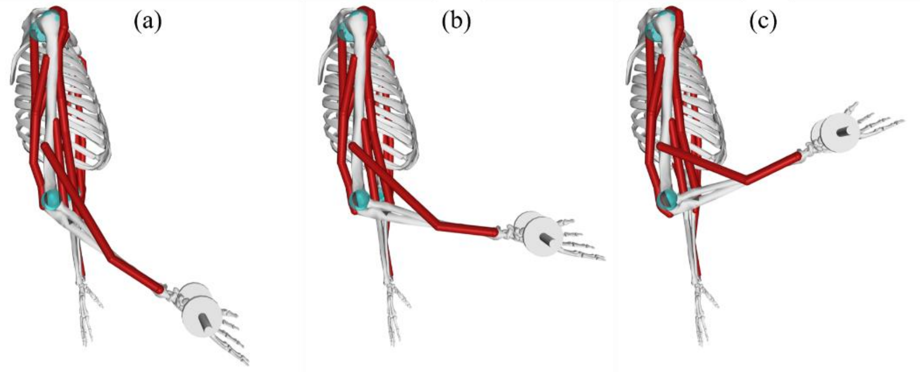

Fig. 3. Upper limbs model during the isometric tests simulation with the dumbbell load: (a) elbow angle 50°, (b) elbow angle 76°, (c) elbow angle 108°.

To numerically evaluate muscles level of activation, the OpenSim Computed Muscle Control tool was used, which reports muscles activation comprise between 0.02 and 1. The minimum value 0.02 is set by default. In Fig. 4, the muscles activation with 4 kg load is reported.

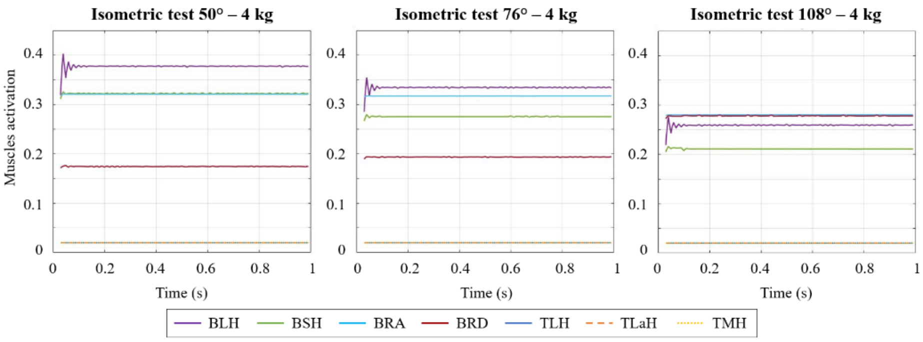

Fig. 4. Simulated muscles activation for Biceps long head (BLH), Bicpes short head (BSH), Brachalis (BRA), Brachioradialis (BRD), Triceps long head (TLH), Triceps lateral head (TLaH), Triceps medial head (TMD), at 4 kg load.

4.3 Comparison and results

For each test and load condition, the average value of the simulated muscles level of activation for all the superficial muscles was obtained. These values were compared with the normalized RMS obtained from experimental sEMG. Fig. 5 reports the comparison between experimental (blue) and simulated (red) muscles level of activation for the three isometric tests (50°, 76°, 108°) and the three load conditions (no load, 2 kg, 4 kg). Differences between simulated and experimental data are reported in Table 1.

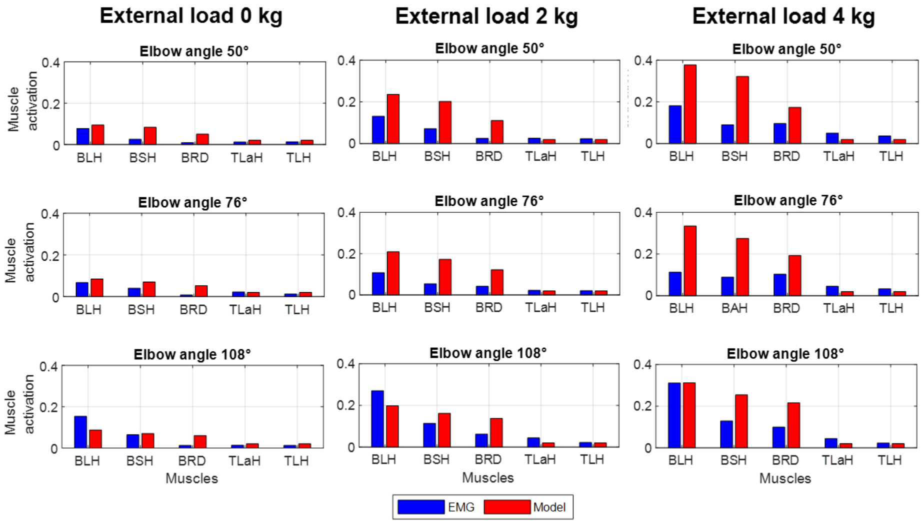

Fig. 5. Comparison of muscles activation obtained experimentally (in blue) and by simulations (in red) in the three isometric tests with the three load conditions.

Table 1. Differences of muscles activation between OpenSim and experimental EMG

Elbow angle (°)	Load (kg)	BLH	BSH	BRD	TLH	TLaH
	0	0.017	0.058	0.041	0.008	0.009
50	2	0.105	0.131	0.085	-0.003	-0.006
	4	0.192	0.233	0.078	-0.017	-0.020
	0	0.017	0.030	0.044	0.008	-0.002
76	2	0.101	0.118	0.080	-0.001	-0.002
	4	0.221	0.186	0.090	-0.013	-0.025
	0	-0.066	0.006	0.048	0.007	0.007
108	2	-0.072	0.048	0.076	-0.002	-0.024
	4	0.001	0.125	0.117	-0.003	-0.024

5 Discussion and conclusion

In OpenSim, existing upper body model have one upper limb only. This research deals with the development of an Opensim upper limbs musculoskeletal model that can be customized according to subject anthropometry and muscles properties. In this preliminary study, the model was customized and assessed comparing the simulated muscles level of activation with data collected using electromyography during isometric tests.

The analysis pointed out many findings. The first aspect is that both the experimental and the computational results showed different muscles contribution according to the elbow angle. The different muscles contribution was even more visible at greater load because of the required higher level of muscles level of activation to counteract the load. For example, in the model for 50° elbow angle, Biceps long head and Biceps short head were the most active muscles; whereas for 108° elbow angle, their activation reduced and Brachioradialis activation increased.

Secondly, extensor muscles (Triceps long head and Triceps lateral head) had a very low level of activation compared to flexor muscles. This result was expected because the adopted position of upper limb and elbow flexion angle required greater level of activation activation of flexor muscles instead of extensor muscles. For OpenSim simulation, extensor muscles level of activation was always equal to 0.02, which means no muscles activation. For the experimental EMG, these muscles activation was negligible for 0 kg of load; whereas when a load was introduced, these muscles showed a small but present activation (< 0.05). This may occur because they were activated to stabilize the position.

Finally, comparing simulated and experimental results, this preliminary study pointed out very small differences in flexor muscles activation in case of no load. In contrast, when the load increased, the differences in flexor muscles activation between simulation and experimental conditions increased. This suggest that for tasks in which a load is involved, other synergic muscles, like Extensor carpi radialis longus and Pronator teres, may be required to better simulate upper limb behavior. An overall model overestimation of the muscle level of activation was highlighted in the several simulated conditions. The reason of this discrepancy from experimental data may due to the model simplification and the limited number of depicted muscles compared to reality.

In conclusion, the current study shows promising results on the right upper limb;

therefore, this procedure deserves to be extended to the left upper limb in order to allow analysis of independent two-handed tasks (for example industrial tasks performed with the assistance of a wearable exoskeleton). Moreover, to validate the model, this assessment will be conducted on a greater number of subjects and in dynamic tests as well. Future perspectives may deal with the implementation of a more complex model with higher number of muscles in order to allow more realistic simulations. The model might be used also in simulations with conditions different from natural loads.

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