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Musculoskeletal simulation of isokinetic exercises: A biomechanical and electromyographical pilot study

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Abstract

Aim of the work was the experimental validation of musculoskeletal models of lower limbs during isokinetic knee flexion-extensions at different angular speeds, using OpenSim® and AnyBody® codes. The adopted approach was: (i) to record the kinematic, kinetic and EMG data on two healthy subjects, (ii) to implement the scaled numerical models of the two subjects within the two codes, (iii) to simulate the isokinetic motions of each subject in each code and (iv) to compare the numerical and experimental activation results in terms of peak, phase and area errors. Results showed a good agreement for extensor muscles, giving an encouraging confirmation about the possibility of using such codes for the evaluation of joint loads.

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1. Introduction

The design of prosthetic materials, aids, orthotics and sports equipment is based on the ability of assessing the stresses on components arising from movements, in turn influenced by anthropometric, physiological and muscle properties of the person involved.

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In particular, the estimation of the joint reactions forces requires the solution of the load-sharing problem [1] of muscle actions converging to the joint under study by means of optimization algorithms. To this purpose, different simulation codes are commercially available such as OpenSim® and AnyBody® : the codes enable the gestures inverse dynamics and the prediction of corresponding loads and muscle, provided that correct assumptions are taken on anthropometry, muscle fibers properties, models of muscle activation and objective functions to optimize [2,3]. The knee isokinetic flexion-extension has been extensively studied in the past for the understanding of the complex behaviour of the knee joint. Differently from the hip joint, where experimental data from in vivo tests on instrumented prosthesis are available since two decades [4], such experiences were carried out more recently for the knee [5,6]. These data can be used for a quantitative validation of numerical models [7], together with the qualitative comparison of EMG experimental signals with numerical predictions of muscle activation.

This paper reports about the experimental motion capture sessions and the following musculoskeletal simulations performed using OpenSim® and AnyBody® codes for the simulation of isokinetic knee flexion-extension movements at different isokinetic speeds.

2. Materials and Methods

The adopted approach was to perform an experimental acquisition of motion and surface electromyography in order to develop subject specific musculoskeletal models scaled on each subject and to perform numerical simulations of their isokinetic exercises for a comparison with the experimental results.

2.1. Instrumentations

We studied the isokinetic knee flexion-extension at 60-120-180-240 °/sec on two healthy subjects (SJ1, SJ2) with a REV 7000 Technogym machine available at the Rehabilitation & Physiotherapy Center CEMES in Padua: after warming up, testers performed at least 4 cycles of maximal intensity for each speed. The machine has a feedback mechanism that allows setting the desired angular velocity and developing, via the lever arm shown in Figure 1, a resisting torque that opposes to the subject's muscular action, recorded as a function of time. The loading arm has a changing length varying with the joint angle, due to the presence of a slider running on a grooved profile, to which the leg is strapped via a padded anklet.



Fig. 1. (a) Technogym REV 7000 isokinetic machine; (b) subject equipped with reflective markers for testing; (c) detail of the loading arm with a ball bearing slider

Motion kinematics and electromyographic activities were detected with a Smart BTS stereophotogrammetric system with 6 cameras working at 60 Hz integrated to 16 EMG channels working at 10 kHz. EMG activities were detected in Rectus Femoris (RF), Vastus Medialis (VM), Vastus Lateralis (VL), Biceps Femoris (BF), Semi Membranosus (SM), Medial Gastrocnemius (GASM) and Tibialis Anterior (TA) muscles. Two Kendall® arbo ecg electrodes of 24mm diameter were applied to each muscle tangent to each other, following the indication of SENIAM guideline [8]. Differential amplifiers connected to the electrodes couples referred to a ground electrode placed on C7 bony prominence. In the subsequent re-analysis, the raw signals were rectified, integrated with a moving window of 150 ms, low-pass filtered at 5 Hz and normalized to the Maximum Voluntary Contraction (MVC) that was performed on the same machine in isometric contractions, taken at each flexion angle with 10° step.

Motion capture analysis gave the trajectories of anatomical markers together with the instantaneous point of application of the force applied to the lever arm by the slider: these data were subsequently used as input of the musculoskeletal models for the solution of the inverse dynamics.

2.2. Numerical Analysis

Musculoskeletal modelling was performed after adapting two models available in OpenSim® 3.2 and AnyBody® 6.0 databases. The kinematic quantities detected experimentally were applied to the models in order to obtain the movement of the body segments; the torque recorded at the machine and the instantaneous lever arm (variable, due to the presence of the slider on the tibial socket) were used to reapply to the model the external forces acting on the tibia. The models were constrained at the pelvis, simulating the combined effect of seat belt and backrest.

Model 3D Gait2392 was used in OpenSim SW: the included muscles are essentially all the muscles of the leg and hip (Figure 2.c). Note that the model does not include the presence of the patella: the knee extensor muscles apply their actions to the tibial tuberosity thanks to a system of "way point", not represented, acting like pulleys.

Model implementation followed different stages: as a first step, the model was scaled to match the anthropometry of each subject. For this purpose, a static posture acquisition was collected in order to obtain the static information about the anthropometry of the subjects. We proceeded by placing virtual marker (pink dots in Figure 2) on the model at the points where anatomical markers were applied to the real subject. The next step was to move the model after imposing the measured kinematics of anatomical markers to virtual markers redefined in the model: the code gets the complete inverse kinematics at each joint minimizing the mean error between the captured trajectories and the virtual markers. The code allows then to calculate the inverse dynamics of the model by adopting as input the complete kinematics previously calculated and introducing the external forces developed at the arm anklet.

The net joint Moments at each joint are obtained after the inverse dynamics solution: this allows the subsequent calculation of muscle activations. The tool that allows this operation is the Control Muscle Compute Tool [2]: to run the CMC, the inverse kinematics and data related to external forces acting on the model are required, by selecting the body segments to which these external loads are applied.

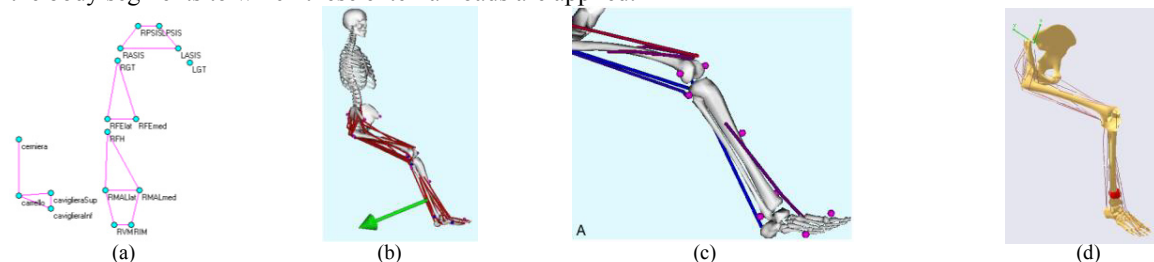


Fig. 2. (a) Schematic of the Markers Protocol adopted in motion capture tests; (b) OpenSim Model used for right leg, with an indication of the force applied on the tibia; (c) detail of muscles activated in extension; (d) Anybody Model used for right leg, showing the tibial socket.

Muscle activations were calculated for each muscle, defined as the ratio between the instantaneous force required to perform the movement and the maximum isometric force provided by the model for each muscle. A unit value corresponds to the development of the maximal isometric force associated to the model. Differently from Anybody, these values are explicitly implemented in [N] in the models: they are not calculated on the basis of information such as the anatomical physiological cross section PCSA, the tension of maximal contraction σ_0 or the angle of pennation.

The model generated in Anybody SW required the adaptation of an existing model of the right leg and pelvis in the Repository 6.3 of Anybody named "Right Leg": it includes the four segments of the pelvis, thigh, leg and foot. Between the segments, different types of geometric constraints are imposed to simulate the hip, knee and ankle joints. Note that, as for OpenSim SW, Anybody SW too applies the simplifying assumption of neglecting the patella. Particular care has then to be taken when studying the knee structures due to the important effect that the patello-femoral joint has in the quadriceps lever arm while the knee extensor muscles are acting. Anybody implementation of muscles are defined with physiological parameters such as the physiological cross-section PCSA, the muscle maximal tension σ_0 and the angle of pennation, with the possibility of adopting different models for

contractile elements (muscle fibers), for the elasticity in series (tendons), and the elasticity in parallel (myofascia). A three element model of muscle was adopted. For the solution of the redundancy problem for multiple muscles converging to a joint, we used the MinMaxSimplex, which considers that muscle, when activated, is able to provide all the isometric muscle strength modulated by a percentage of activation. The two other criteria, the linear and the quadratic [2], were not adopted in this study. Simulation results are expressed as ratio between the instantaneous force and the maximum force that the muscle can develop at the length and speed of contraction at which it is working.

3. Results

The results of tests of isometric contraction showed a clear difference of torque values applied during extension (max value 200 Nm) and flexion (max value 70 Nm), and different trends of Torque-Angle curves, not shown for brevity. The dynamic torque curves recorded at different speeds as a function of the angle of flexion-extension were used as external loads input to the musculoskeletal simulations.

The numerical simulation results obtained for Vastus Lateralis (VL) and Medial Hamstring (SM) on Tester 1 at 240°/sec isokinetic flexion-extension are shown as examples in Figure 4: comparison is possible between experimental EMG measurements normalized to MVC (black curves) and numerical results of four cycles performed after simulation with OpenSim (blue curves) and Anybody (red curves). Simulations performed at the maximum speed of execution were chosen in order to include the ability of muscle models to introduce the Force-Speed dependence response in muscle force simulations. Also other speeds were analysed in a similar way.

For data comparison, both the experimental results and the numerical outputs were further studied in order to recognize the four cycles. For each muscle, within each cycle, maximum activations were recorded and average values together with Standard Deviation were calculated among the four cycles. Given the peak values, the time instants in which, during the cycle, the muscle reached its maximum activation were also recorded. Finally, the area subtended by the signal of muscle activation for each cycle was also calculated, with mean and Standard Deviation values within the four cycles. The direct comparison between the experimental results and the numerical ones required the introduction of error percent indexes, based on the previously described parameters, associated with the four different isokinetic tests for the two testers.

The Peak Error was defined as the % difference between NUMerical peaks and EXPerimental ones, referred to the EXPerimental activation (1):

$$PeakErr\% = 100 \cdot \left(\frac{NUM_peak - EXP_peak}{EXP_peak} \right) \quad (1)$$

The Phase Error was defined as the difference between the instant of the numerical peak and the experimental peak instant, referred to the cycle duration for normalization (2). The numerical signal is anticipated if the phase shift is positive while it is delayed if the sign is negative:

$$PhaseErr\% = 100 \cdot \left(\frac{t_{NUM_peak} - t_{EXP_peak}}{T_cycle} \right) \quad (2)$$

The Area Error was defined as the % difference between numerical Area and experimental ones, referred to the Experimental Area:

$$AreaErr\% = 100 \cdot \left(\frac{NUM_A - EXP_A}{EXP_A} \right) \quad (3)$$

The criteria adopted for the signal comparison are described in Figure 3. Results of all muscles at 240°/s for Subject 1 are reported in Table 1 & 2, with values lower than 10% error shown in bold.

4. Discussion

Aim of the work was the validation of musculoskeletal simulation outputs against experimental collected EMG data. The main limitation of the work was the small number of subjects and the reduced amount of results that we were able to include in this paper for brevity.

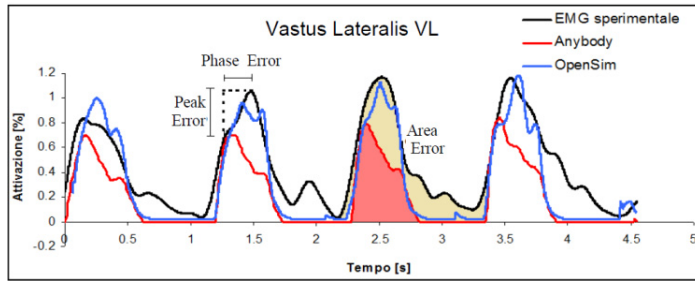


Fig. 3. Representation of Error Indexes introduced for Experimental and Numerical results comparison.

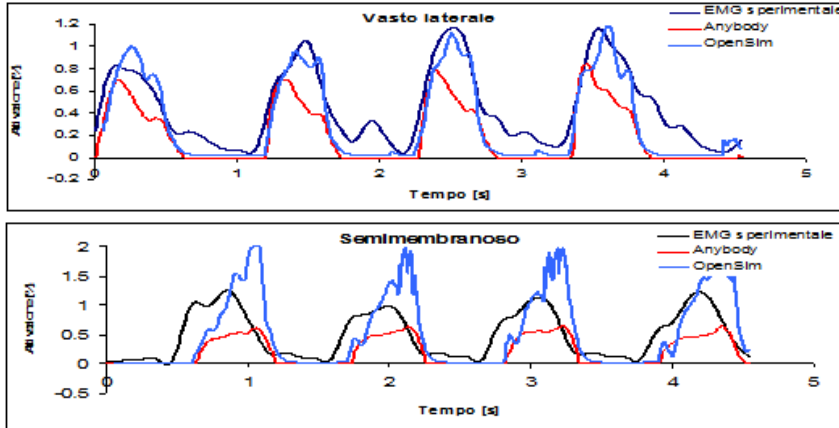


Fig. 4. Results of numerical simulations obtained with the two codes of an extensor (VL) and a flexor (SM), Tester 1 at 240 °/sec of isokinetic flexion-extension, compared with the corresponding experimental values (in black) normalized to the maximum voluntary contraction MVC.

Table 1. OpenSim and experimental EMG comparison at 240°/sec, averaged over 4 cycles (values lower than 10% error are shown in bold).

Peak Error, [%]	SM	BF	RF	VM	VL	GM
Mean	74.33	-7.57	54.84	1.01	2.71	87.89
SD	31.07	36.06	61.25	14.12	22.13	93.28
Maximum peak phase shift [% of cycle duration]						
Mean	-16.24	-17.1	-20.2	3.95	-2.2	-35.64
SD	5.34	25.22	15.26	9.37	11.06	9.3
Area Error [%]						
Mean	8.91	-42.42	3.51	-33.74	-27.58	-40.46
SD	9.29	17.47	31	3.02	11.38	30.33

Table 2. Anybody and experimental EMG comparison at 240°/sec, averaged over 4 cycles.

Peak Error, [%]	SM	BF	RF	VM	VL	GM
Mean	-44.82	-41.76	36.22	2.6	-27.09	-44.82
SD	11.37	9.81	24.39	12.87	13.85	6.17
Maximum peak phase shift [% of cycle duration]						
Mean	-15.38	-27.88	-0.41	13.77	7.62	-33.44
SD	3.56	16.52	3.41	6.51	11.42	7.99
Area Error [%]						
Mean	-55.78	-57.71	-14.25	-36.65	-52.03	-66.28
SD	6.47	6.15	20.01	2.14	7.41	6.77

From the analysis of Figure 4 and Tables 1-2, the good correspondence between simulation and experimental measurements can be appreciated for both codes at the extensor muscles VM, VL and RF: simulations with OpenSim reported a tendency to instability for some bundles like SM and GASM (shown by irregular peaks of activation, Figure 4). The behavior of the flexor muscle BF was satisfactory, although it tends to be underestimated in the peak and phase errors; for the other flexor muscles, SM gave unsatisfactory result, especially with OpenSim. In OpenSim, some muscle simulations were affected by the appearance of irregular peaks: this phenomenon was related to the low maximal strength implemented for these muscles based on data taken from cadaver [2], as already reported in recent literature. The results reported for Tester 1 at 240 °/sec were generally extensible at lower speeds of contraction and also to Tester 2. When analyzing the areas under the curves of activation limited to concentric contractions, the calculated error was lower and produced more significant comparison with the numerical data (which do not provide co-activation muscle).

Overall, Anybody code lead to lower errors in terms of peak, with a tendency, however, to a greater peak phase shift if compared to OpenSim.

5. Conclusions

The work is an attempt to carry out a qualitative validation of musculoskeletal simulation tools, currently being widely available and used by the scientific community. Once the predicted values of muscles can be validated against some experimental data, the values of joint loads typically unknown can be used with greater awareness for assessing stresses at bones and ligaments in joints that are being studied in orthopedics and rehabilitation. For a proper validation of simulations, some error indexes were proposed, focusing on activation intensity and timing. The obtained results showed a good correspondence for some of the muscles acquired (VM, VL, RF). The two codes were on average comparable to correct simulation, although AnyBody® presented a more stable behavior than OpenSim®. Similar also was the numerical-experimental correlation among the two subjects involved.

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