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Validation of a subject specific 3-actuator torque-driven model in human vertical jumping.

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Abstract— **In this study, a forward dynamic subject specific 3-actuator torque-driven model of the human musculoskeletal system was created based on measurements of individual characteristics of a subject. Simulation results were compared with experimental vertical squat jumping with and without adding weights. By analyzing kinematic and kinetic experimental data at the instant of the toe-off for the same initial conditions, it was shown that a simple computer simulation using a suitable cost function could reproduce the real task performed by humans. This investigation is the first step in a wider project that will incorporate elastic components, and that will evaluate the advantages of the individual subject approach in modeling.**

I. INTRODUCTION

Nowadays computer simulation has been invaluable in furthering our understanding of the mechanics and physiological behavior of human movement. For example, sport scientists used simulations to better understand human motion, by optimizing sport techniques of common tasks such as walking, running, and vertical jumping [1] or even by optimizing more complex movements such as gymnastic and athletics abilities [2]. Generally, one could use two different approaches: (1) considering average muscle characteristics to provide general predictions, where the model is usually constructed from generic parameters and thus it does not represent any of the subjects it is compared against; (2) investigations based on single subject where model parameters are equal to those measured on a given subject and compared with the subject's best performance. The computational approach enables the control of many test conditions, avoiding lengthy sessions in the lab. This approach also allows to independently control the individual variables that affect performance and various training conditions.

Here, one-subject's characteristics were incorporated into simple computer simulations to address questions about his individual response to different jump conditions. The goal of this paper was to propose and validate a subject specific 3-actuator torque driven 2D jumping simulator to examine actual performance of different conditions in squat jump exercises with and without adding weights.

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II. METHODS

A. Forward Simulation Model

A subject specific whole body model was built using Working Model 2D (WM2D®, Design Simulation Technologies, Inc. USA). The model consisted of four linked rigid segments representing upper body (head, trunk and arms together), thighs, shanks and feet (Fig. 1). Three torque generators drive simulations: hip, knee and ankle joints. The model was limited by an assumption of monoarticularity. The motivation is to create a simple model in order to investigate the macroscopic features of human performance on vertical jumping with and without adding weights. Foot-ground interface was modeled using two linked bodies, one rigid component representing the segment of the foot from the heel to the ball and one elastic standard component of WM2D called *flexbeam* to represent, close to the reality, the flexion of the foot at the ball (Fig. 1).

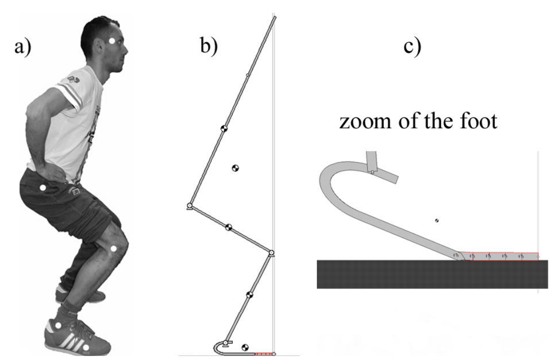

Figure 1. a) Subject position and markers location, b) four linked rigid segments model, c) foot details: the part from the ball to the end of tips was modeled using the flexbeam WM2D script.

The complete foot was in contact with a rigid body that simulated a force platform. A vertical slot was attached to the end of the *flexbeam* component in order to avoid sliding of the foot during propulsive phase between the whole body and the ground.

Mechanical constraints limited the range of motion (ROM) of each single joint with respect to anatomical ROM.

Anthropometric characteristics and inertia moments were calculated from the subject according to Chandler equations [3]. Animation step of the simulation (SIM) was set at 60Hz and the integrator method used by WM2D was Kutta-Merson.

B. Experimental Data

Kinematics, vertical ground reaction force (GRF_z) and surface electromyography (sEMG) data were synchronized and collected for a series of bilateral jumps by an individual male athlete (29yrs, 1.74m, 63Kg) and the best performance in terms of jump height was analyzed for each condition. The participant was asked to perform three different types of squat jumps starting from approximately 1.57 rad posterior knee joint angle:

- Maximal height squat jump body weight (SJ_{bw})
- Maximal height squat jump with an added 40% of the body weight ($SJ_{+40\%}$)
- Maximal height squat jump with an added 80% of the body weight ($SJ_{+80\%}$)

Kinematics were collected using a Vicon Nexus motion analysis system (Oxford Metrics, Oxford, UK) sampling at 120 Hz. Markers were placed on the right side of the body on head temple, greater trochanter, malleolus and foot ball. Raw data were low pass filtered at 6Hz using a 4^{th} order zero lag butterworth filter according to Winter recommendations [4]. GRF_z data were recorded using Kistler platform sampling at 960Hz and raw data were filtered using a 4^{th} order zero lag butterworth low pass filter at 3Hz. sEMG activities (SMART-BTS, Milan, Italy) were recorded (960 Hz frequency) on the subject's right side for the tibialis anterior (TA), soleus (SOL), gastrocnemius medialis (GA) rectus femoris (RF), vastus lateralis (VL), the biceps femoris long head (BF) and gluteus (GL). The skin was shaved and cleaned with alcohol to ensure low impedance. The interval between electrodes was 2 cm. In accordance with the recommendations of International Society for Electromyography and Kinesiology [5], raw sEMG signals were first bandpass filtered between 10 and 400 Hz and then full-wave rectified and filtered using a 10Hz low-pass filter to obtain a linear envelope.

Maximum torque (T, N.m) profiles of the hip, knee extensors, and ankle plantar flexors were determined via isokinetic dynamometer (Biodex,USA) at different angles (θ, rad) and concentric angular velocities (ω, rad/s). Positional data were also corrected to ensure real bone alignment [6]

C. Muscle Model

Muscle-tendon complex (MTC) is generally categorized into a three-component assembly: series elastic element (SEE), contractile component (CC) and parallel elastic elements (PEE). Muscle force is governed by two relationships: (1) muscle tension increase and decrease depending on fibre length that is known as a parabolic length-tension relation [7]; (2) muscle tension decreased as the velocity of shortening increased generating a relation know as tension-velocity [8].

However, according to the nature of the squat jump and, especially a squat jump with added weight, the model considers only CC, in order to simplify its conception. In our model CC is represented by rotational actuators, and the converted features are torque-angle (T, θ) and torque-angular velocity (T, ω) relationships at hip, knee and ankle joints.

D. Model Input Data

Torque data were fitted [9] using a 4-parameter hyperbolic function for the concentric phase between T and ω (equation 1), where T_0 is the isometric torque, ω is the angular velocity, ω_{max} is the angular velocity at which the curve reaches zero torque, and ωc defined by the vertical asymptote ω = -ωc of the classic Hill hyperbola.

$$T(\omega) = \frac{C}{(\omega c - \omega)} - Tc \quad (if\, \omega \geq 0) \qquad (1)$$

Where $Tc=T_0\,\omega c/\omega_{max}$, $C= Tc(\omega_{max}+ \omega c)$

The torque-angular relationship was represented by a nonlinear quadratic function [9,2] showed in equation 2, where k_2 = width curve, θ = angle, θ_{opt} = optimal angle.

$$T(\theta) = 1 - k_2(\theta - \theta_{opt})^2 \qquad (2)$$

Active state, i.e. muscle activation (recruitment and firing rate of α-motoneurons), even when maximal is never instantaneous and was controlled in the model by a simple activation ramp function showed in equation 3. Therefore, the fraction of torque, which can be exerted at any time t, is determined by multiplying the maximal torque calculated from the torque generator parameters by an activation *Act*. Each activation profile ramps were forced not to exceed the range between 0 and 1 (see appendix section Fig. 3). Detailed information is described elsewhere [9].

$$Act= 0+(z)^3\cdot(6z^2-15z+10) \qquad (3)$$

$$z = \frac{t-d}{r}$$

Where *t* is time, *d* is the delay of activation between joints and *r* is the rise time for building force. The optimal solutions that best matched a subject's actual SJ_{bw}, $SJ_{+40\%}$ and $SJ_{+80\%}$ were calculated with a brute-force optimization algorithm using a cost-function to minimize SIM vs actual performance (equation 4) including hip, knee and ankle angles and the vertical velocity of the hip at toe-off for the SJ_{bw} and adding the vertical velocity of the barbell for the $SJ_{+40\%}$ and $SJ_{+80\%}$. For the velocity at toe-off a value for the weighting (50) was decided as 0.17 rad angle equivalent to 0.2m/s velocity error (equation 5).

$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{si-ai}{ai}\right)^2}{n}} \qquad (4)$$

$$S = 50 \cdot \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{si-ai}{ai}\right)^2}{n}} \qquad (5)$$

Where *S* is score; *si* is value of variable *i* from simulated performance; *ai* is value of variable *i* from actual performance and n is number of variables in objective function part. The brute-force algorithm was set using five variables: *Hr* (hip ramp force), *Kr* (knee ramp force), *Ar* (ankle ramp force), *Kd* (knee onset), *Ad* (ankle onset). Ramp force variables were allowed to vary in a range between 0.090s and 0.284s, onset variables between 0 and 0.020s.

III. Results

Quantitatively, the model corresponds well to real jump conditions. SIM gave a set of activation patterns that best matched actual performances (Table I.). A proximal-to-distal sequence of muscle activation (from hip to knee to ankle) confirmed data from literature [1]. Joint displacements from the start position to the instant of the toe-off showed a good correspondence. Kinematic data (θ) at the instant of toe-off are shown in the appendix section (Table III.). However, quantitatively the general tendency of all SIM conditions was to underestimate actual performances:

A. Squat Jump $_{bw}$

Jump height of the SIM SJ_{bw} was 32.2% lower than the actual SJ_{bw}, SIM SJ_{bw} propulsive phase was 22.1% lower than the real propulsive phase, the RMSE expressed as percentage (%), of the peak GRF_z, was 15.3% (Table II.).

B. Squat Jump $_{+40\%}$

SIM $SJ_{+40\%}$ showed the greater percentage error compared with its actual performance between all three conditions. Jump height of the SIM $SJ_{+40\%}$ was 38.6% lower than the actual $SJ_{+40\%}$, SIM $SJ_{+40\%}$ propulsive phase was 29.4% lower than the real propulsive phase, the RMSE (%), of the peak GRF_z, was 18.9% (Table II.).

C. Squat Jump $_{+80\%}$

The RMSE (%), of the peak GRF_z for the SIM $SJ_{+80\%}$ was 9.8%, the lower error between GRF_z over all conditions (Fig. 1). Jump height difference of 30.8% also was the lower difference for jump height between all conditions. Finally the SIM $SJ_{+80\%}$ propulsive phase was 25% lower than $SJ_{+80\%}$ (Table II.).

TABLE I. Optimal activation parameters.

SIM conditions	*Hr*	*Kr*	*Ar*	*Kd*	*Ad*
	Activation parameters t(s)				
SJ_{bw}	0.101	0.176	0.154	0.005	0.012
$SJ_{+40\%}$	0.091	0.166	0.136	0	0.006
$SJ_{+80\%}$	0.093	0.091	0.108	0.002	0.003

Data set obtained from matching simulation at 60Hz for SJ_{bw} , $SJ_{+40\%}$ and $SJ_{+80\%}$. Hr, Kr and Ar are the rise time for building torque of hip, knee and ankle joints respectively. Kd and Ad are the onset delay of the knee and the ankle joints with regard to the hip joint.

TABLE II. Measured values and simulation results.

Actual	***GRF_z*** ***Peak (N)***		***Jump height*** ***Height (m)***		***Propulsive phase*** ***Time (s)***	
SJ_{bw}	1450		0.239§		0.334*	
$SJ_{+40\%}$	1674		0.163§		0.401*	
$SJ_{+80\%}$	1797		0.104§		0.568*	
SIM	***Peak (N)***	***RMSE (%)***	***Height (m)***	***Error (%)***	***Time (s)***	***Error (%)***
SJ_{+bw}	1297	15.3	0.162	32.2	0.260	22.1
$SJ_{+40\%}$	1537	18.9	0.100	38.6	0.310	29.4
$SJ_{+80\%}$	1610	9.8	0.072	30.8	0.426	25

§ Jump height was calculated using the flight time method; * the start of the propulsive phase was located when the force value was greater than three time the deviation standard of the average value of the start equilibrium position before to jump.

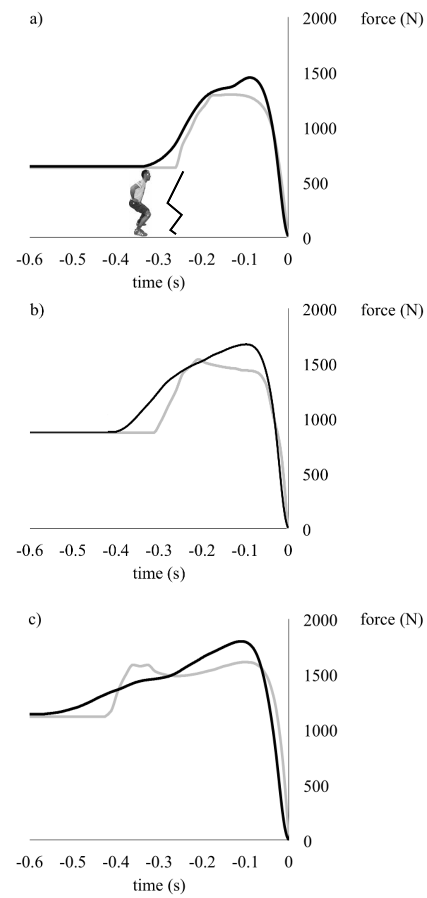

Figure 2. Vertical ground reaction force curves. Black line is the actual performance, gray line is the SIM. a) SJ_{bw}, b) $SJ_{+40\%}$, c) $SJ_{+80\%}$. Subject picture and stick diagram, in the *a* panel, show the starting position for actual and SIM performance, respectively. The subject picture and the stick diagram are synchronized with the instant of the propulsive phase start. 0 = instant at the toe-off.

IV. Discussion

The purpose of this work was to create a model and compare it with a specific subject for testing its validity. Although we built a simple model, according to other musculoskeletal models, a proximo-distal activation sequence was observed [1]. The corresponding result of SIM GRF_z (Fig. 2) showed a good matching. However, in all simulations the propulsive phase was faster than in reality. This could be explained by the lack of SEE structures in the model. They generally slow down the rise up of the force [10], which is useful to produce more muscle power since the beginning of the movement occurs at low velocity when the muscle is stronger. That could be the reason why the peak GRF_z of all SIM occurs earlier than reality–and lower jump heights were obtained. Also, we did not include biarticular muscles in the model. It has been shown that biarticularity is crucial in order to achieve an optimal jump height in modeling. Not taking that into account could result in less than 50% of the actual jump height [11]. In contrast with that prediction, our model was able to achieve more than the 61% for all SIM conditions with regard to the actual performance. Further, the SIM $SJ_{+80\%}$ was the more accurate condition, showing that the heavier the barbell weight, the more accurate the model. However, the simulator is strongly influenced by input data, and it is possible that the subject used in this study was more familiar and capable to express his strength limits during dynamometer testing sessions.

In summary, a specific 3-actuator torque driven model could be a successful tool to investigate and determine different training strategies of a single athlete, since it represents specific muscle characteristics of the subject. This is the main important feature of this model, as it could potentially predict squat jump (with and without weights) performances. Here, we considered just concentric movements; we are currently working on a set of experiments and simulations on large applications to confirm the preliminary data presented in this paper. However, this model is a first step of an extensive project about modelling applied to strength and conditioning performance. The next challenge now is to validate a further developed jumping model including eccentric, isometric and concentric phases, with the presence of elastic structures.

APPENDIX

TABLE III. KINEMATIC DATA.

		Start position θ (rad)		Toe-off instant θ (rad)	
		actual	SIM	actual	SIM
SJ_{bw}	*Hip*	1.58	1.58	2.95	3.12
	Knee	1.55	1.55	3.05	3.14
	Ankle	-0.49	-0.49	0.60	0.34
$SJ_{+40\%}$	*Hip*	1.73	1.73	2.93	2.83
	Knee	1.61	1.61	3.01	3.14
	Ankle	-0.48	-0.48	0.56	0.30
$SJ_{+80\%}$	*Hip*	1.74	1.74	2.94	3.01
	Knee	1.51	1.51	3.06	3.14
	Ankle	-0.53	-0.53	0.58	0.32

Kinematic angular data expressed in radians of the actual performance against simulations at the starting position and at the instant of the toe-off.

Jump height was calculated using the fly time method, which is described in equation (6) where v is the velocity at the toe-off instant, g is 9.81 and $tflight$ is the fly time phase in seconds.

$$v = \frac{g \cdot tflight}{2} \qquad (6)$$

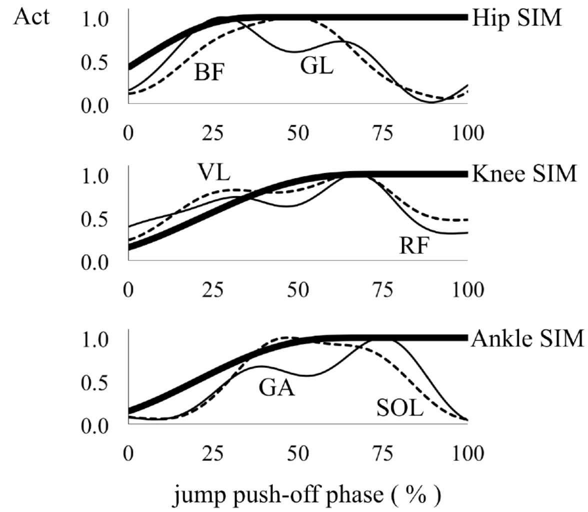

Figure 3. Activation profiles example (SJ_{bw}). Bold lines represent SIM results. Activations are shown as function of percentage jump push-off phase. Toe-off = 100%. (GL, BF, RF, VL, GA, SOL = sEMG envelopes low-pass filtered at 7Hz).

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