Portuguese Journal of Sport Sciences
11 (Suppl. 2), 2011

MODELLING THE BEHAVIOUR OF SERIES ELASTIC ELEMENT DURING IMPULSIVE MOVEMENTS

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A Hill type model which incorporates the effects of the activation, elasticity, and pre-history during force production has been developed. Its implementation required a balance between the lengths and forces produced by the muscle tendon unit and its elements. Knowing the muscle tendon length from the joint angles in the beginning of the muscle contraction, its constituent parts as well as forces, moments and subsequent kinematic phases were determined. It was concluded that the introduction of the tendon seems to be relevant for force enhancement and muscle efficiency.

KEY WORDS: modelling, muscle, force enhancement, series elastic element, contractile element.

INTRODUCTION: Modelling and prediction of muscle response in real time in a variety of phenomena has been a great challenge in biomechanics and motivated a large research investment in last years. A variety of mathematical and experimental models with different level of complexity (Hill, 1938; Huxley, 1957; Zahalak, 1990), representing muscle tendon unit (MTU) has been developed, but very few describes the muscular action that occurs during the stretch shortening cycle of short duration such that of athletic jumps.
Usually, impulsive actions involve a counter-movement in which the muscles stretch initially, following by a shortening to accelerate the body or segment (Ingen Schenau, 1997).
Force enhancement following stretching is a well known and widely observed phenomenon both in isolated fibres as well as in a variety of muscles (Alexander, 1988; Epstein, 1998; Herzog, 1997). In this process series elastic element (SEE) behaves as a management element of the energy produced. As stated in the literature, the mechanism of energy storage and reutilization works optimally when the muscular shortening is supported by the effect of SEE which contributes to a more efficient muscular contraction (Alexander, 1988).
The purpose of this study was to (i) determine the influence of SEE in force production in different regimens; (ii) simulate mono and biarticular muscles (iii) represent and describe the phenomena that determine muscle function during the stretch shortening cycle (SSC).

METHODS: A planar three rigid segment model, foot, shank and tight, was developed in *Matlab/simulink/Simmechanics* environment (The MathWorks Inc., USA). Segment lengths were obtained from measurements on the subject. Each segment represents a composition of a rigid and a soft part. In this study, parameters defining wobbling coupling forces were based on Gruber et al. (1998) model scaled using the segment length and mass to the model inertial properties.
Two muscles, the *soleus (So)* and *gastrocnemius (Gas)*, were assumed to provide the plantarflexion torque with *Gas* also crossing the knee joint. A Hill-type model comprising a contractile element (*CE*), *SEE* and parallel elastic element (*PEE*) describing the behaviour of each muscle have been developed being the velocity and active state the input. It was introduced in the model: (i) activation in the concentric phase of force velocity relationship (*FV*); (ii) modelling of the eccentric phase (iii) implementation of the mechanisms associated with the potentiation (*pot*), and (iv) explicit implementation of the primary mechanism of potentiation i.e., the interaction between muscle and tendon.
MTU force was calculated multiplying the function force-length ($0 \leq FL \leq 1$) with the function force velocity *FV* ($0 \leq F_{vel} \leq 1.6$) having the force enhancement result from the previous

stretching, also considered as factor (1+pot) with ($0 \leq$ pot ≤ 0.6) (Boehm, 2001; Conceição, 2005).
The *FL* was modelled as a quadratic function (van Soest et al., 1993) and the *FV* relationship was described by a hyperbolic function for concentric contractions considering the active state as described by Chow and Darling (1999). Optimal fibre length (L_{CEopt}) and pennation angle from Winters and Woo (1990). The SEE was assumed to have quadratic stiffness and a 5% stretch at maximum isometric force (Finni & Komi, 2002). SEE slack length obtained as the difference between L_{CEopt} and stretch deformation and muscle tendon unity length (Conceição, 2005). Moment arm was modelled as a quadratic function of joint angle as given by Visser et al. (1990) for the *Gas* at the knee and Rugg et al. (1990) for the *So* and *Gas* at the ankle. Total length of the muscle-tendon unit (L_{MTU}) was obtained from data reported by Friedrich & Brand (1990). Both moment arm and muscle-tendon unit length were scaled to the subject based on standing height.
During force production and its transmission in impulsive movements tendon acts like a filter which smooth and delay the force propagation. Tendon was explicit introduced on the model with the aim to adjust the reply times of the system as it can be seen:

$$\begin{cases} F_{SEE}(L_{SEE}(t), L_{MTU}(t)) = F_{CE}(V_{CE}(t), L_{CE}(t), t, act(t)) + F_{PEE}(L_{CE}(t)) \\ L_{SEE}(t) + L_{CE}(t) = L_{MTU}(t) \end{cases} \quad (1)$$

A mono and biarticular muscles of the lower leg, *So* and Gas were simulated during a realist (DJ_r) (data from experimental measurements) and idealized depth jump (DJ_i), with constant and variable activation. For the idealized depth jump the knee angle was kept constant while changing the ankle angle between -30º and 60º, corresponding to a plantarflexion (stretching) and plantar extension (shortening) movement. Anatomical zero for the ankle joint was determined as described by Rome (1996).
Simulations performed were: (i) *CE* (only muscle) during DJ_i with constant activation; (ii) *MTU* (muscle and tendon) during a DJ_i with constant activation; (i) *CE* (only muscle) during a DJ_r with variable activation; (ii) *MTU* (muscle and tendon) during a DJ_r with variable activation. Energy dissipation was calculated by integrating the muscle strength in order to the shortening of the *MTU* for the simulations above described.

RESULTS: Having as input the activation, angle and velocity the behaviour of the L_{MTU} and L_{CE} of both muscles were simulated considering different contraction regimens, i.e. eccentric, isometric and concentric. Fig 1 shows the simulation of *So* and *Gas CE* during a DJ_i with constant activation (*act*=1), where it can be seen the forces produced and variation of the muscle length. For the *Gas* the knee was kept constant at 160º.

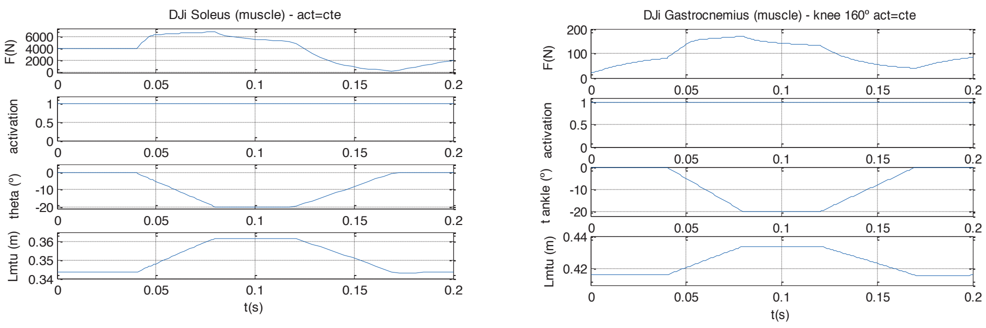

Figure 1: *So* and *Gas* CE (only muscle) simulation during a DJ with constant activation. Theta_knee= 160º.

Trying to understand the role of the series elastic elements during a DJ_i a simulation of the *MTU* was carried out, keeping constant the initial conditions above presented (Fig 2).

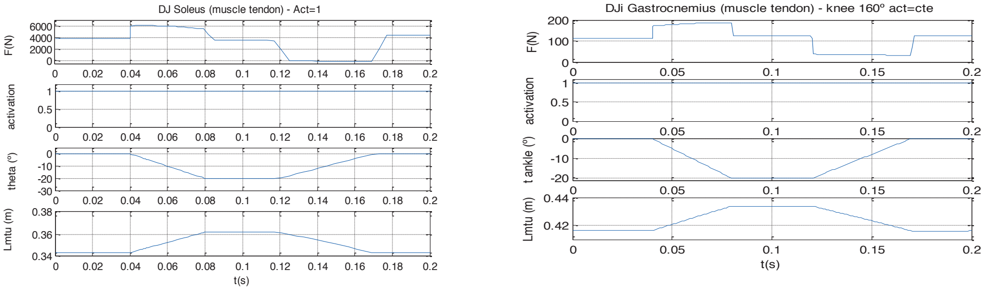

Figure 2: *So* and *Gas* MTU simulation during a DJ_i with constant activation. Theta_knee = 160º.

Then CE during a DJ_r with variable activation was simulated. Ankle angles data were obtained from depth jumps performed by a long jumper and activation from an electromyogram during a long jump, Fig 3.

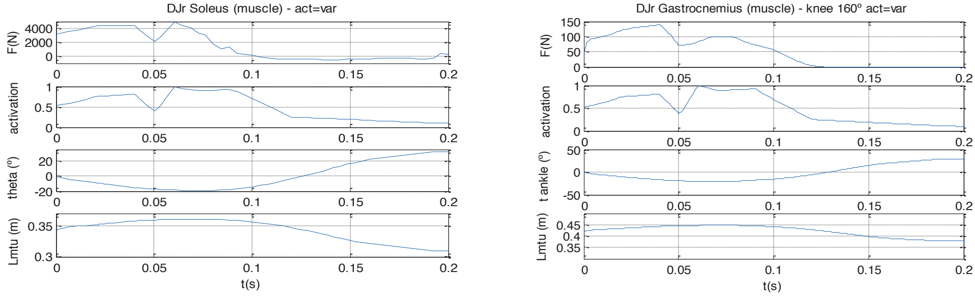

Figure 3: *So* and *Gas* CE simulation during a realist DJ with variable activation.

Finally tendon was introduced and *MTU* simulation during a DJ_r with variable activation was performed (Fig 4).

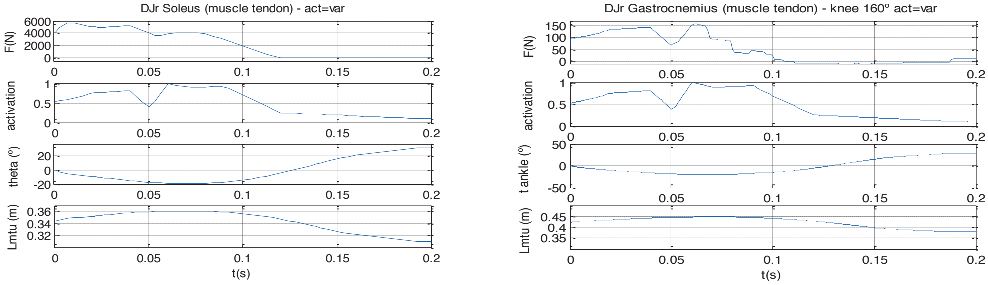

Figure 4: *So* and *Gas* MTU simulation during a realist DJ_r with variable activation.

Concerning the energy dissipated for the CE and MTU by the *So* during a DJ_i with constant activation, it was obtained a figure of 69.53 and 67.79 J and for *Gas* 2.6 and 1.5J.
A model to simulate impulsive actions was developed. This study aims to know the role of series elastic element on force production during impulsive actions. Results show a lower force development when the *CE* is simulated without the contribution of the tendon, both for constant or variable activation as well as for idealized or realist joint angles (Fig 1, 2, 3, 4). Soleus develops for constant and variable activation, forces of 6154 N and 4.900N, whilst a figure of 6852 N and 5600 N is observed when the *SEE* is introduced in the simulation. Similar results were obtained for the *CE* and *MTU* muscle *Gas*. For DJ_I it was obtained values of 138.6 and 157.9 J, whereas for DJ_r it was 169.6 and 187.4 J, respectively. These

results seems to be in agreement with the literature when it says that the *SEE* works as a spring (Griffiths, 1991), that store and release energy. It is also observed, when the *MTU* is simulated, a force increasing during eccentric phase followed by an exponential decay in the isometric phase of the contraction followed by a more deep decay in the concentric phase but never attaining zero, which agree with experimental results (Cook & McDonagh, 1996). Comparing the results obtained by the *CE* when it was simulate alone to that when tendon is introduced (*MTU*), an instantaneous force increase is observed in the eccentric phase followed by decay in the isometric phase where values are similar to the starting point, and finally values around zero in the concentric phase. Force enhancement is not observed and the reason seems to be related to the fact that SEE is not considered. Since they are responsible for the storage and release of the energy, the increase in force during concentric phase will depend on the interaction between tendon and muscle. To point out the relevance of series elastic element for force enhancement and efficiency, minor energy dissipation was obtained when *SEE* was introduced in the simulation relatively to that with contractile element only.

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