POWER ASSESSMENT OF INDIVIDUAL LEG MUSCLE GROUPS BY MULTISTRUCTURAL ANALYSIS OF SYMMETRIC VERTICAL MAXIMUM EFFORT JUMPS

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A method is introduced which permits the quantification of individual muscle work contributions occurring in the joints of a segmented body model in all phases of bi-legged vertical jumping. In this way, the evolution in time of the performance criterion can be monitored and deficiencies in the muscle groups involved can be detected. It is also shown that point mass body models are inadequate for relating jumping performance and muscle power contributions.

KEY WORDS: performance criterion, total energy, multi-segment model, muscular work contributions

INTRODUCTION: The biomechanical analysis of bi-legged maximum effort vertical jumping performance is used extensively for evaluating the myodynamic capabilities of the lower body musculature (Bobbert, Huijing, and van Ingen Schenau, 1987; Bosco, Luhtanen, and Komi, 1983; Frick, Schmidtbleicher, and Wörn, 1991; Hatze, 1998; Kirkendall and Street, 1986; etc.). In discussing these performance tests it is essential to distinguish between point mass body models and segment-structure body models. As will be demonstrated below, the energetic situation and hence the interpretation of the results is different for the two types of body models.

POINT MASS VERSUS SEGMENT-STRUCTURE BODY MODELS: In the point mass body model, the total body mass is assumed concentrated in one point located at the body center of mass. This model can perform only translatory but no rotatory motions. In contrast, segment-structure body models are, by definition, collections of segment assemblages and therefore move according to multibody dynamics which includes both translations and rotations of the interlinked segments. Because segment-structure models also permit the computation of their center-of-mass positions for specific configurations, their predictions can be compared directly with those of point mass models. The **performance criterion** to be maximized in bi-legged vertical maximum effort jumping is given by

$$\tilde{J} = \rho_z(\tau) + \dot{\rho}_z^2(\tau)/2\mathrm{g} \qquad (1)$$

where ρ_z is the vertical (z-)component of the center-of-mass (c.m.) position vector $\underline{\rho}$, $\dot{\rho}_z$ is the corresponding velocity component, τ is the moment of take-off, and g = 9,81 m.s^{-1}. In other words, the sum of the c.m. height at take-off plus the flight distance of the c.m. from the take-off position to its culmination point after take-off is to be maximized.

Because the location of the maximum of a function is invariant under multiplication of this function by a constant and the subtraction of another constant, the performance criterion (1) may be converted into an equivalent one by multiplying (1) by the body weight Mg and subtracting resting energy terms. Thus (1) becomes

$$J = \mathrm{Mg}\left[\rho_z(\tau) - \rho_z(0)\right] + \tfrac{1}{2}\mathrm{M}\left[\dot{\rho}_z^2(\tau) - \dot{\rho}_z^2(0)\right] = \int_0^{\tau}\left[\mathrm{Mg}\,\dot{\rho}_z(\mathrm{t}) + \mathrm{M}\ddot{\rho}_z(\mathrm{t})\dot{\rho}_z(\mathrm{t})\right]\mathrm{dt} \quad , \qquad (2)$$

which is seen to be the increment during the vertical jump of the sum of the vertical potential and kinetic energy of the body mass located in the mass centroid. It can also be shown that this is equivalent to the functional shown as the second expression in (2).

The important point to recognize is that the height criterion (1) has been converted into an energy criterion (2), that is, the maximization of jumping height is equivalent to maximizing the increment in vertical potential and kinetic energy of the body mass model.

These vertical energy increments are, of course, produced by actions of the muscles spanning the joints involved. In other words, we require relationships that relate muscle work done in vertical jumping to the energy increments (2). An application of d'Alembert's principle to complex multi-body systems (Wittenburg, 1977) reveals that the sum of all work done over the period τ by all muscles and passive structures in all υ body joints involved plus the work done by all non-gravitational external forces $\underline{F}_j$ and torques Q_j^E (constraint forces and torques do no work) must be equal to the increment in mechanical energy of the system consisting of n segments, that is,

$$\sum_{k=1}^{\upsilon} W_k(t) + \sum_{j=1}^{n}\left[\int_0^t \underline{F}_j(u)\dot{\underline{\rho}}_j(u)du + \int_0^t Q_j^E(u)\dot{q}_j(u)du\right] = \sum_{j=1}^{n}\left[\Delta E_{ktj}(t) + \Delta E_{krj}(t) + \Delta E_{pj}(t)\right], (3)$$

where $\dot{\underline{\rho}}_j$ are the velocity vectors of the segmental mass centroids, $\dot{q}_j$ are the angular velocities in the respective joints, and $\Delta E_{ktj}, \Delta E_{krj}, \text{and } \Delta E_{pj}$ denote respectively the increments of the segmental translational kinetic energies, the rotational kinetic energies, and the potential energies. The sum of the segmental potential energies is equal to the potential energy of the whole system and equivalent to that of the point mass model as expressed by the first energy term in equation (2).

In the present case of bi-legged vertical jumping the use of a two-dimensional segmented body model is a good approximation. Because there are no external forces $\underline{F}_j$ or torques Q_j^E in addition to gravity and constraints on the feet active, these terms may be equated to zero. Furthermore, the work contributions $W_k(t)$ of muscles and passive joint structures may be determined by inverse dynamics methods. The work is produced in the joints between thorax and pelvis $(W_s(t))$, in the hip $(W_h(t))$, the knee $(W_k(t))$ and the ankle $(W_a(t))$. Hence the **evolution in time of the performance criterion (2)** may be expressed as the energy function for a segment-structured body model

$$\Phi(t) = W_s(t) + W_h(t) + W_k(t) + W_a(t) + \left\{\tfrac{1}{2}M\left[\dot{\rho}_z^2(t) - \dot{\rho}_z^2(0)\right] - \sum_{j=1}^{n}\left[\Delta E_{ktj}(t) + \Delta E_{krj}(t)\right]\right\}. \quad (4)$$

METHODS: Fig. 1 displays the four angles q_{15} (pelvis-thorax angle), q_{16} (hip angle), q_{17} (knee angle), and q_{18} (ankle angle) that need to be measured (by flexible goniometers in the present case) during the vertical jumping motion. Left-right symmetry is assumed. All other angular coordinates of the 17-segment, 21-degrees-of-freedom model (Hatze, 1980) used are assigned constant values because hands and arms are assumed stationary with respect to the thorax, as indicated in Fig. 1. Also shown in Fig. 1 are the ground reaction forces F_y and F_z , and the center-of-pressure function a_y, which quantities must also be measured during the vertical jump. Angle measurements and force plate data were synchronized. In addition, the body segment parameters (Hatze, 1980) also need to be determined for the specific subject in question. With these data, the individual muscular work contributions $W_k(t)$ to the performance criterion (2) can be computed with the aid of a complex computer program.

RESULTS AND DISCUSSION: Six healthy physical education students (average age 23.8 years) of which three were males consented to participate as subjects in the present study. After a short training period designed to get the subjects accustomed to perform bi-legged maximum effort vertical jumps with their hands resting on their hips, each subject performed after warming up a series of three jumps of which the best (maximum flying height of the center of mass) was analysed and evaluated. An example of hip and ankle joint work contributions for a male subject (rower, 22 years, 80.13 kg body mass, 1.86 m standing height) is shown in Figure 2. The work contributions are normalized to the body mass.

As can be seen from Fig. 2 there is a substantial absorption of mechanical energies by the muscles during the deceleration phase of the downward motion (negative work contributions). This trend is, of course, reversed during the upward motion, where muscle power is used to propel the body upwards. The present example has been chosen because it demonstrates an interesting but somewhat atypical case of excessively large mechanical energy absorption during the downward motion of which apparently only a fraction is returned during the upward movement phase. This is also the reason why the non-representative knee joint work contributions are not shown. The obvious performance deficit of this subject manifested itself also in the results obtain from the simultaneously performed point mass model analysis: the relative jumping height of 34 cm and the normalized total maximum

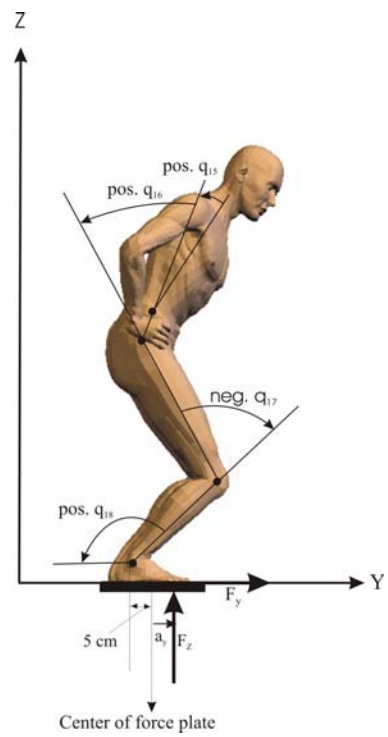

Figure1 - Diagrammatic representation of observable quantities during bi-legged vertical jumping. Details in the text.

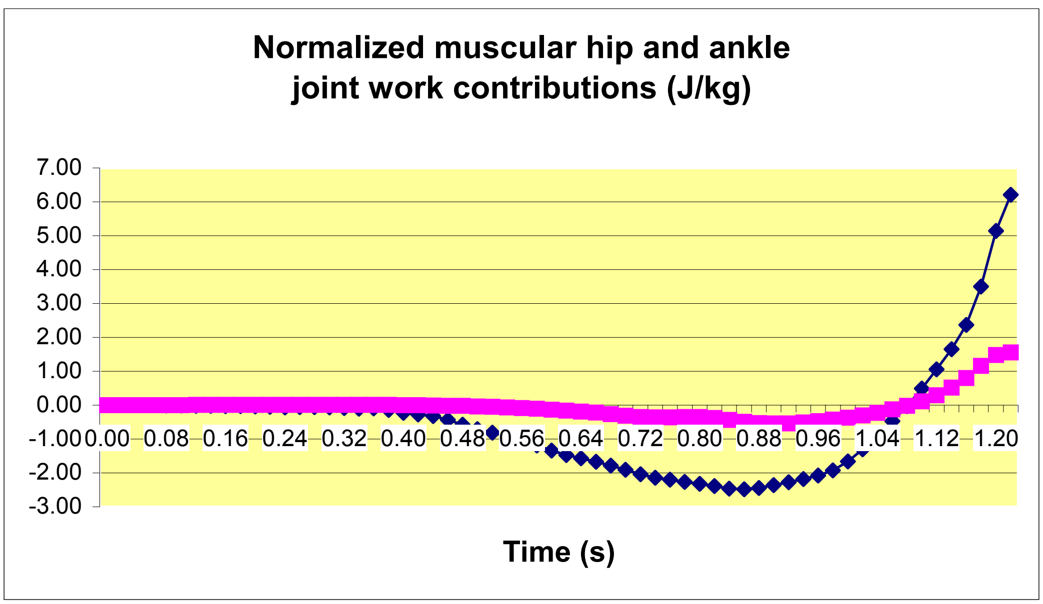

Figure 2 - Evolution in time of the normalized muscular work contributions $w_h(t)$ and $w_a(t)$ in the hip joints (rhombs) and the ankle joints (squares) respectively.

jumping power of 49 W/kg body mass are far below the average values of athletes with comparable training status. One of the reasons could be the leg movement pattern of rowing which, in some respects, resembles that of bi-legged vertical jumping but is much slower.

CONCLUSION: Because segmental energy forms such as rotational and translational energies in non-vertical directions must also be generated by the muscle groups involved in producing a bi-legged vertical jumping motion but do not contribute to vertical translational energies, a straightforward relationship between muscular leg power output and the jumping performance as measured by the point-mass-model does not exist, as is obvious from relation (4). In other words, point-mass-model evaluations (Bosco et al., 1983) of bi-legged vetical jumping performances are not reliable. On the other hand, the present method using a segment-structure body model and inverse dynamics techniques permits the quantification and monitoring of muscle work contributions occurring in the joints during the vertical jump and thereby a performance assessment of the muscular torque generators involved. This is especially useful for practical applications in performance testing of athletes.

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