A MECHANICAL MODEL TO ESTIMATE LEGS MUSCLE STIFFNESS COEFFICIENTS IN HORSE DURING JUMPING

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The purpose of present study was to use a simple mechanical model to estimate horses' legs muscles stiffness coefficients in jump height during jumping a spread fenceof 140 cm high. A digital camcoder was used (25 Hz) along with Ulead Studio program in order to obtain time, related distance, and various angles in horses' legs data. The total jump distance and time of flight for each horse were measured with a precision of 10^{-2} m and 10^{-2} s respectively. Biomechanical formulae have been established in order to evaluate the muscles stiffness coefficients. Three groups of leg muscles; serratus ventralis, biceps brachii, and radial carpal extensor were considered in this study and their stiffness coefficients were successfully estimated.

Key words: horse, modelling, muscle stiffness coefficients, take-off

INTRODUCTION:

So far few studies have evaluated horse kinematics and kinetics; Shahbazi and Khosravi (2007) and the CG kinematics of horses jumping over relatively small fences (=1m high) reported by Powers and Harrison (1999, 2000), and jumping over a water jump (=4.5m wide) reported by Clayton et al., (1996). An early study (Clayton and Barlow, 1989) examined the effect of fence dimensions on the limb placement of jumping horses, but no analysis was conducted on the CG kinematics and estimation of muscles stiffness. Shahbazi (2004) and Shahbazi and Erfani (2005) modeled human legs and reported a reasonable stiffness coefficients values. The take-off kinematics of jumping horses in puissance competition was investigated and reported by Powers (2005). The body position and kinematics of horses' centre of gravity at take-off are important factors determining jump outcome. Unlike human athletes, horses are unable to significantly alter their body positions during jumping and therefore need to raise their CGs substantially, in order to clear the fence. The take-off is crucial to the jump outcome. Jumping requires the horse to raise its centre of mass high enough for all of its body parts to successfully clear the height and width of a fence. The jump should be viewed as an increased part of the suspension phase or an elevated canter stride as it occurs between the stance phase of the fore and hind limbs, for this reason jumping is mostly performed whilst cantering. So far there was no biomechanical investigation of horses' muscles kinetics in jumping. The main aim of this study was to model and estimate horses' legs muscles stiffness in the linear CG kinematics and kinetics of take-off through establishing biomechanical relationships.

METHODS:

Video recordings (25 Hz) were obtained of two top horses and jumping over a spread fence of 1.4m height and 1m wide. A single Sony camera was set up 10m from the centre of the spread fence. The field of view measured about 6m wide and encompassed one full approach stride and the take-off phase. Video recordings were then transferred into ULead Studio program in order to measure the different angles of horse leg's joints (angles between fibula-femur and pelvis) in two distinct positions and time sequences. One rider (52 kg of mass) rode both horses in order to have the same method of jumping.

MODELLING:

As is depicted on Fig.1, horse's legs were simulated by sticks (B) representing the pelvis, femur, and tibia bones and the muscle group in contraction and extension are presented in (C). General data about leg's bones and muscles are also presented on (D) and (E). In order

to achieve relationships for different groups of leg's muscles stiffness, the muscle model on (C), helped us to establish different relationships for muscle's force components on X and Y axes (Eq.1-4) and the elastic energy of muscles (Eq.5-6). The muscles lengths were measured at horse's normal stance then were estimated in two different positions; in contraction Δl and in extension $\Delta l'$ The muscle elastic forces were considered as ($K\ \Delta l$) and ($K\ \Delta l'$) in two positions. K_1, K_2, and K_3 were considered as stiffness coefficients for serratus ventralis muscle, biceps brachii muscle and radial carpal extensor muscle respectively. Each force had its X (horizontal) and Y (vertical) components by knowing the angles of joints. Θ_1, Θ_2, Θ_3 and Θ'_1, Θ'_2 and Θ'_3 are the angles between pelvis and femur, femur and tibia, and tibia and cannon bone respectively in two positions.
Δl_1, Δl_2, Δl_3 and $\Delta l'_1$ $\Delta l'_2$ $\Delta l'_3$ are the length of serratus ventralis muscle, biceps brachii muscle and radial carpal extensor muscle respectively in two positions.

Force components on X and Y axis in contraction position:

$$k_1\, \Delta l_1 \cos\theta_1 + k_2\, \Delta l_2 \cos\theta_2 - k_3\, \Delta l_3 \cos\theta_3 = 0 \qquad (1)$$

$$-k_1\, \Delta l_1 \sin\theta_1 - k_2\, \Delta l_2 \sin\theta_2 - k_3\, \Delta l_3 \sin\theta_3 - Mg = 0 \qquad (2)$$

Force components on X and Y axis at take-off position:

$$k_1\, \Delta l'_1 \cos\theta'_1 - k_2\, \Delta l'_2 \cos\theta'_2 + k_3\, \Delta l'_3 \cos\theta'_3 = Ma_x \qquad (3)$$

$$k_1\, \Delta l'_1 \sin\theta'_1 + k_2\, \Delta l'_2 \sin\theta'_2 + k_3\, \Delta l'_3 \sin\theta'_3 - Mg = Ma_y \qquad (4)$$

Energies:

$$\tfrac{1}{2} k_1 (\Delta l_1)^2 + \tfrac{1}{2} k_2 (\Delta l_2)^2 + \tfrac{1}{2} k_3 (\Delta l_3)^2 = Mgh_{cm} \qquad (5)$$

$$\tfrac{1}{2} k_1 (\Delta l'_1)^2 + \tfrac{1}{2} k_2 (\Delta l'_2)^2 + \tfrac{1}{2} k_3 (\Delta l'_3)^2 = \tfrac{1}{2} Mv^2 + Mgh'_{cm} \qquad (6)$$

Combining these relations yielded the following relationships for muscles stiffness $\mathbf{K_1}$, $\mathbf{K_2}$, and $\mathbf{K_3}$:

$$\mathbf{k_3} = -M\,[v^2 A (\Delta l_2)^2 + 2A\eta g - \lambda_1 (a_x + a_y)] / (\lambda_1 C + \lambda_3 A) \qquad (7)$$

$$\mathbf{k_1} = M\,[v^2 C (\Delta l_2)^2 + 2C\eta g - \lambda_3 (a_x + a_y)] / (\lambda_1 C + \lambda_3 A) \qquad (8)$$

$$\mathbf{k_2} = [k_1\, \Delta l_1 \cos\theta_1 + k_3\, \Delta l_3 \cos\theta_3] / (\Delta l_2 \cos\theta_2) \qquad (9)$$

In which λ_1, η, λ_3 and A and C have the following values:

$$(\Delta l'_1)^2 (\Delta l_2)^2 - (\Delta l_1)^2 (\Delta l'_2)^2 \equiv \lambda_1$$

$$(\Delta l'_3)^2 (\Delta l_2)^2 - (\Delta l_3)^2 (\Delta l'_2)^2 \equiv \lambda_3$$

$$h'_{cm} (\Delta l_2)^2 - h_{cm} (\Delta l'_2)^2 \equiv \eta \qquad (10)$$

$$\Delta l'_1 \sin(\theta'_1 + \theta'_2) + \Delta l_1 \sin(\theta_1 + \theta_2) \equiv A$$

$$\Delta l'_3 \sin(\theta'_3 + \theta'_2) + \Delta l_3 \sin(\theta_3 + \theta_2) \equiv C \qquad (11)$$

RESULTS AND DISCUSSION:

Two horses jumped the fences at the height of 1.4m, three times each, the data of which are represented in Table 1. The same rider was riding both horses and his mass was 52kg and was included in total mass of the horses. The first two columns data are dedicated to the horses mass and their take-off velocity, which was reported by Shahbazi and Khosravi (2007), while the next six columns are dedicated to the muscles lengths at contraction and take-off positions respectively. Columns 9, 10, and 11 represent the gravity and horizontal and vertical horse accelerations. Column 12 and 13 represent the centre of mass height in two different positions and the next six columns represent the different angles of different legs joints. Inserting these data into the established formulae for K_1, K_2, and K_3, their numerical values are given in last three columns. Our findings show that the heavier horse (600 kg of mass) had larger stiffness coefficients (23 times larger in K_1, 2 times larger in K_2 and finally 12 times larger in K_3) than the other horse, although it's initial velocity and CG acceleration components were lower. This could probably come from the fact that its rider was not able to conduct the horse properly. All the muscles' measures were measured by a specialist and at stance position. The landing and take-off points were marked by experienced persons and flight time and distance were also measured with appropriate precisions Shahbazi and Khosravi, (2007).

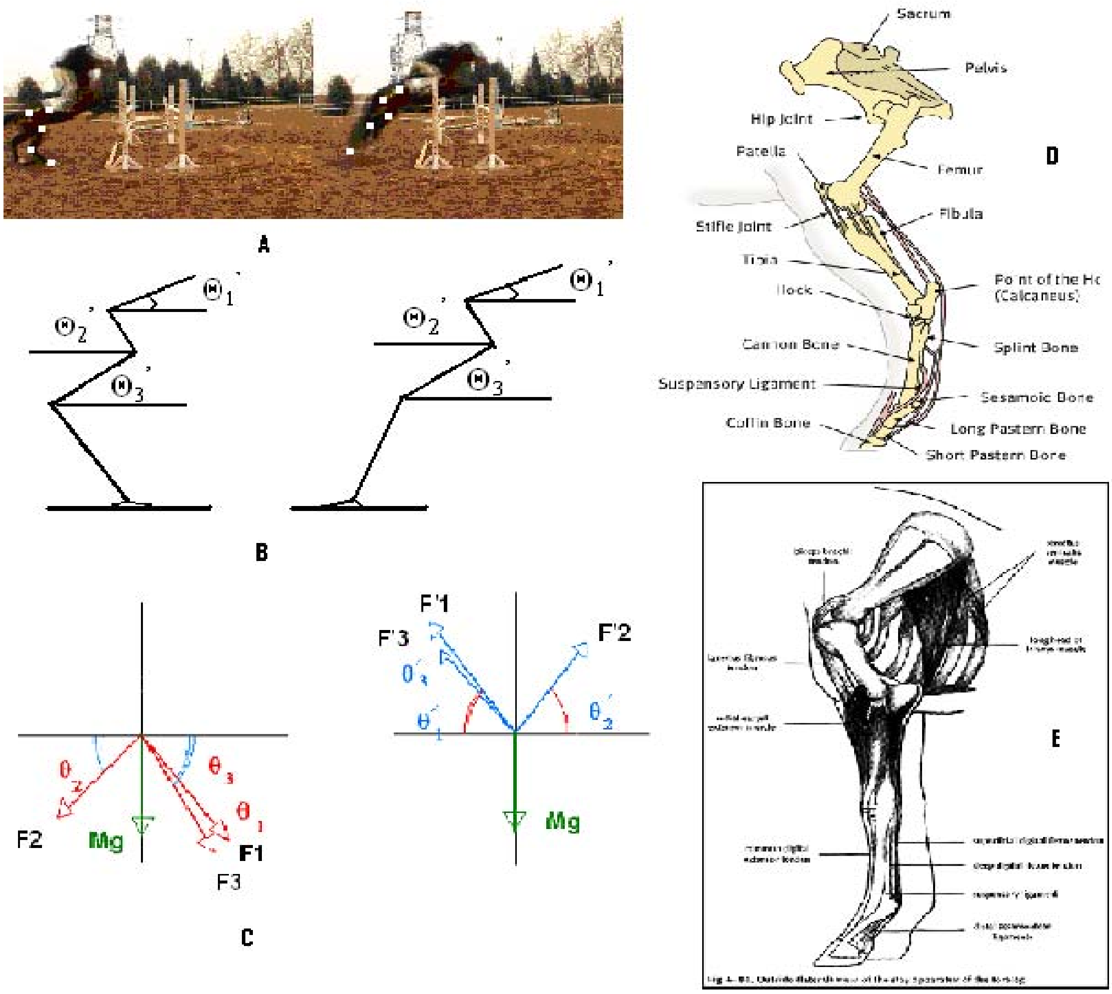

Figure 1: (A) Horse jumping two extreme positions: preparing for jumping; muscles in contraction, and Take-off, where muscles are at extension; (B) simulation of leg's pelvis, femur, and tibia bones; (C) muscles at contraction and extension; (D) and (E) leg's bones and muscles.

Table 1- Muscles, centre of mass, accelerations, angles and stiffness measures of two horses

M	V	Δl_1	Δl_2	Δl_3	$\Delta l_1'$	$\Delta l_2'$	$\Delta l_3'$	g	a_x	a_y	h_{cm}	h'_{cm}	θ_1	θ_2	θ_3	θ'_1	θ'_2	θ'_3	k_1	k_2	k_3
400 kg	5.4 m/s	30 mm	25 mm	20 mm	40 mm	35 mm	22 mm	9.76 m/s²	27.9 m/s²	30 m/s²	1.74 m	2.0 m	60 °	220 °	58 °	133 °	47 °	139 °	3.9 10^5	2.8 10^5	1.8 10^6
600 kg	4.4 m/s	35 mm	22 mm	20 mm	38 mm	25 mm	5 mm	9.76 m/s²	20.2 m/s²	24 m/s²	1.69 m	1.9 m	53 °	208 °	50 °	120 °	57 °	130 °	9.1 10^6	5.6 10^5	2.1 10^7

CONCLUSION:

A mechanical modeling has been introduced to evaluate the stiffness coefficients of horses' legs muscles at take-off in jumping a spread fence. Mathematical formulae have been established to calculate these muscles stiffness coefficients. By using this method, these kinematic variables at take-off, riders, trainers and the owners of horses would be able to recognize their horse's muscles stiffness and take necessary actions to improve horse jumping. The model needs first filming and then measuring the time of flight of CM, the different legs joint angles in two position, and the muscles measures in different positions and finally the use of the above formulae to achieve horses' legs muscles stiffness coefficients.

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