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RELATIVE CONTRIBUTION OF THE JOINT MOMENTS TO THE ANGULAR ACCELERATION OF THE LOWER LIMB IN HOPING EXERCISE

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The purpose of this study was to estimate the ability of joint moments to transfer mechanical energy through all the leg segments during a cyclic hoping exercise. The technique was applied to data from 4 triathlon athletes to characterize the relative ability of the lower limb joint moments to accelerate the ankle, knee and hip joints. Our findings show that the strategies used to maintain the same jumping height rely on the balance between the joint net moments to guarantee the acceleration of the joints. While the ankle and knee moments reduced their contribution to accelerate the ankle and the knee joints, the hip moments increased their participation.

KEY WORDS: induced acceleration, joint moments, jumping, inverse dynamics.

INTRODUCTION: Muscles have critical participations in the performance of a motor task. As Zajac (2002) mentioned, «muscles redistribute the net mechanical energy of the body segments because each muscle force causes reaction forces throughout the body with the net effect being to accelerate some segments and decelerate others». This means that a muscle acts in all joints and segments, even joints it does not span and segments to which it is not attach to. This phenomenon, also called induced acceleration is a precious tool to analyze in greater detail and directly quantify a muscle/muscle group contribution to a specific motor task. The magnitude of these accelerations is a function of both the intensity of the muscle forces as well as the displacement of the joints. Analyses of induced accelerations have been mainly used with normal and impaired gait (Siegel, 2007, Goldberg & Kepple 2009), in order to study the changes in muscle contributions to motion. However, most dynamic human movements in sports activities involve cyclic stretch-shortening actions with maximal mechanical power production, so this technique should be of benefit in analyzing the different contributions of lower limb muscle groups over a time period during cyclic exercise. In order to perform the induced acceleration analysis of a cyclic hoping exercise until exhaustion, this study uses a model based on Kepple's work (Kepple 1997), according with the principles referred by Zajac and Gordon (Zajac 1989). These principles lie on the fact that the moments produced by muscle forces around a joint will accelerate all joints of the body. This can be achieved by expressing the equations of motion in the following form:

$$q = M^{-1}T + M^{-1}C + M^{-1}G + M^{-1}F \qquad \text{(Eq. 1)}$$

where q is the joint accelerations matrix, M^{-1} is the inverse inertia matrix (where the segments inertial parameters and center of mass positions are taken into account), T is the joint moments matrix, C is the Coriolis terms matrix, G is the Gravitational terms matrix and F is the external forces matrix. Setting C, G and F terms to zero allows us to obtain the accelerations produced only by the joint moments (Kepple 1997).

$$q = M^{-1}T \qquad \text{(Eq. 2)}$$

To isolate the contribution of one particular joint moment to the acceleration of all the joints of the model implies the assumption that those other joints have moments and stiffness equal to zero. Accelerations' magnitude is dependent not just on the moment magnitude but also on the configuration of the body segments. Therefore, the purpose of our study was to use a similar induced acceleration analysis (IAA) to estimate the ability of joint moments to transfer mechanical energy through all the leg segments during a cyclic hoping exercise. We also wanted to understand how this energy transfer changes due to specific fatigue. The technique was applied to data from 4 triathlon athletes to characterize the relative ability of the lower limb joint moments to accelerate the ankle, knee and hip joints.

METHODS: Four elite triathletes (weight: 62.4±5.3 kg and height: 1.7±0.1 m) performed a sequence of unilateral jumps with their dominant lower limb until exhaustion. Informed consent was given by each subject prior to testing and the work has been approved by the ethical committee of the Faculty of Human Kinetics. To establish a control parameter for the jump height, a squat jump (SQJ) was performed prior to the hoping task. The minimum height of all jumps was 80% of the maximum height achieved in the SQJ. The subjects performed the jumps on a contact mat placed on the top of a force plate, facing a computer monitor where they could see the feedback of their jumping height. They were instructed to keep their hands on their waists to minimize arm motion because the head, arms and trunk were modeled as a single segment (Kepple, 1997). Task failure was considered when the subjects couldn't achieve the minimum required height. Two trials were selected for analysis: one in the beginning of the sequence (referred as "start") and the other right before the end of the task (referred as "final"). Motion capture was collected with 10 cameras Qualisys (Oqus-300) operating at 200Hz. 24 reflective markers and 4 marker clusters were used for the reconstruction of eight body segments (trunk, pelvis, thighs, shanks and feet). GRF was collected with a Kistler force plate (type: 9865B). Computed variables (Visual 3D Basic RT, C-Motion, Inc., Germantown, MD) included joint angular displacement, joint velocities and net internal joint moments. The results were processed with a lowpass 4^{th} order Butterworth filter with a frequency cut of 6 Hz. Ankle, knee and hip joint induced angular accelerations were computed using the IAA Module (Kepple, 1997, Siegel, 2007). This step was repeated using separately ankle, knee and hip joint moments as the input for the IAA computation. The IAA was performed at all frames of the ground contact phase of each jump. The ankle was designed as a universal joint (plantar/dorsi flexion and inversion/eversion), the knee as a revolute joint [flexion/extension (flex/ext)] and the hip as a spherical joint [flexion/extension, abduction/adduction (abd/add) and internal/external (int/ext) rotation]. The inertial properties of the segments were based on Hanavan's study (Hanavan 1964).

RESULTS AND DISCUSSION: In a general way, there is a decrease in the angular amplitude and angular velocity flexion and extension peaks of the joints. Joint moments also decreased, especially ankle moment, with the exception of the hip flex/ext moment that increased. It could be a possible adaptation of the system to maintain the same mechanical output. Interestingly, both abd/add and int/ext rotational moments have a smoother pattern when compared with the flex/ext moment. The accelerations and GRFs induced by the ankle, knee and hip flex/ext moment are reported in Figs.1 and 2. Analyzing joint by joint, the ankle was highly accelerated by the knee and ankle moments during braking phase reaching a peak of 600 and -800 deg/s^2, respectively. The hip contribution remains the same although it increases in the final hops with a peak value of 225 deg/s^2 right after the foot contact. The abd/add and rotational moments of the hip did not contributed significantly to the ankle flex/ext acceleration (results not shown) but they accelerated the ankle into inversion/eversion and rotation more substantially in the first hops. The three joint moments contribute to the knee acceleration, in particular the ankle and knee moments (peak value of -500deg/s^2 and 650deg/s^2, respectively). Concerning hip acceleration, again ankle and knee moments were the main contributors reaching peak values of 400 and -400 deg/s^2, respectively. Each moment contributed to accelerate the joints but over time that contribution decreased for the ankle and knee moment and remained more or less constant for the hip flex/ext moment.

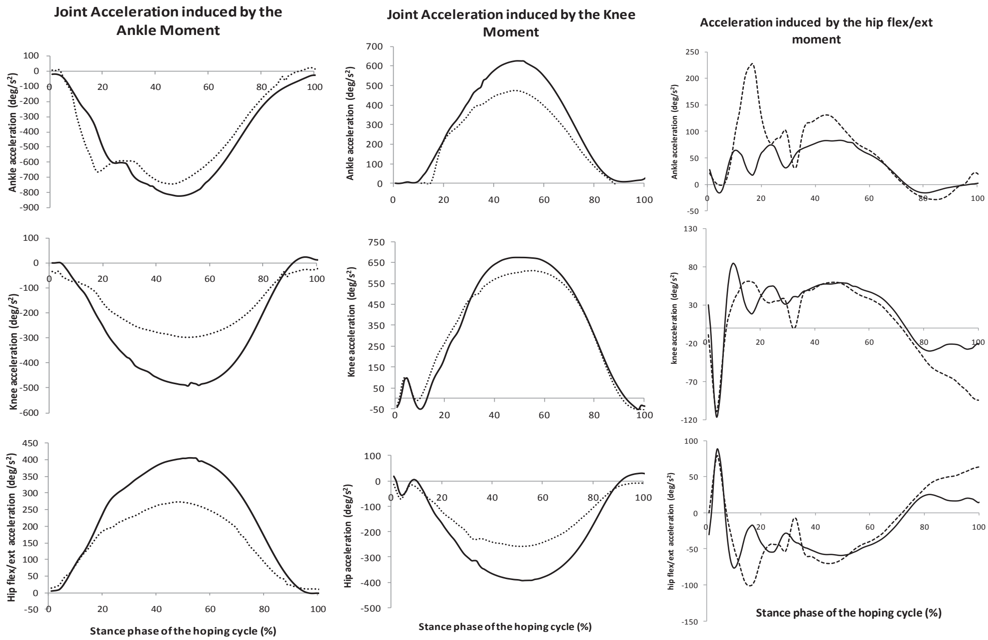

Figure 1: Joint angular accelerations induced by the ankle, knee and hip internal net moments. First hoping sequence (solid line) and last hoping sequence (dotted line). All the variables concern to the sagital plane of motion.

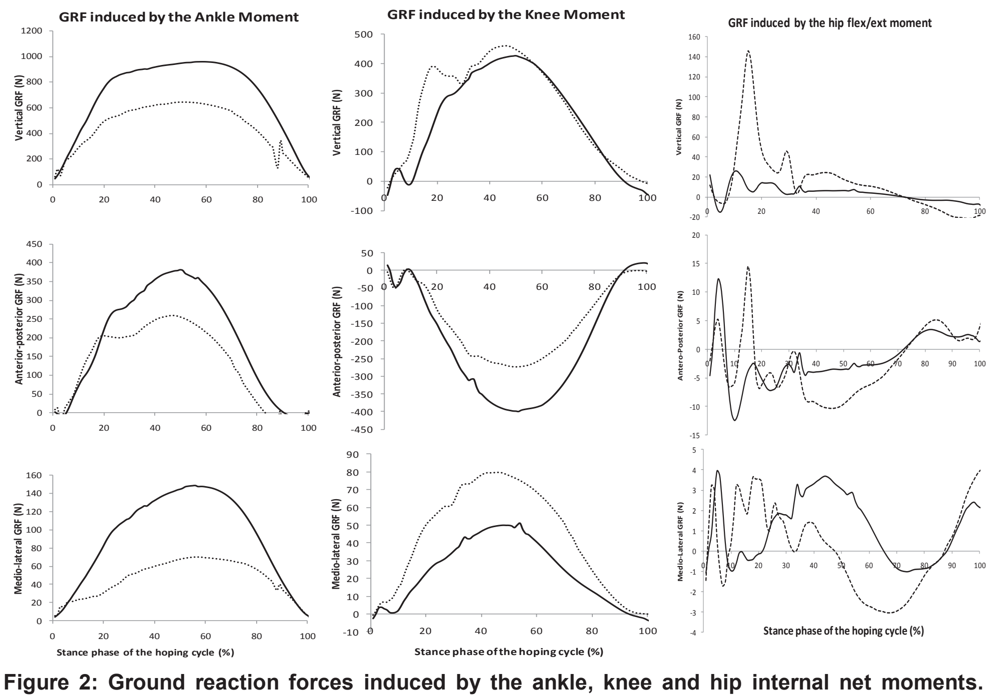

Figure 2: Ground reaction forces induced by the ankle, knee and hip internal net moments. First hoping sequence (solid line) and last hoping sequence (dotted line). All the variables concern to the sagital plane of motion.

However, in the final jumps hip moment increased its contribution to accelerate the ankle, therefore compensating the decrease of the ankle and knee joint moments contribution to maintain the jumping height (performance criterion). Looking at the vertical component of the GRF, the ankle induced nearly 1000N, the knee moment contributed 400N, hip moments had a lesser contribution. The anterior-posterior GRF component had a clearly contribution of the ankle and knee moments which decreased along the jumping task and it was observed two patterns for the contribution of the hip abd/add moment: some subjects presented a positive curve pattern whereas other presented a negative curve, both decreasing in time. This effect may be due to the jumping technique adopted by each subject, pushing the floor in opposite directions to maintain their bodies always in the same position. The medio-lateral component of the GRF was generated mainly by the ankle moment (140N) and interestingly, the knee and hip rotational moments increased their contribution in the last hoping sequence.

CONCLUSION: Our findings showed that the strategies used to maintain the same jumping height rely on the balance between the joint net moments to guarantee the acceleration of the joints. While the ankle and knee moments reduced their contribution to accelerate the ankle and the knee joints, the hip moments increased their participation. The hip rotational moment contribution to the vertical GRF is negative. A possible reason for this is the fact that even with the plantarflexors very active (and consequently producing a positive GRF), the athletes simultaneously flex their hips and the hip flexors would reduce the GRF produced by the plantarflexors muscle group (producing a negative induced GRF). This effect was even marked in the final hops. Fatigue leads to failure after repeated application of stresses, and changes in tendon elastic properties may have a positive effect on the dynamics of the muscle-tendon complex during stretch-shortening cycle exercise. Muscle force generating ability is compromised by the tendinous structure compliance, since it influences the length and shortening velocity of the muscle, according to the force-length-velocity relationship. Lichtwark's (2005) studies with Achilles tendon show that the majority of the strain occurs in the tendon compared with the contractile component. If the tendon experiences an elevated elongation, the muscle component may be less affected and could actuate at a lower shortening velocity. Benefiting from the force-velocity relationship, GM would then be able to produce more force. In vertical jumping the hip is commonly assumed to be a pin joint which has only one degree of freedom because sagital plane is assumed to dominate the performance of the motor task (Zajac, 1989). However, in this case of unilateral vertical jumping, the hip joint was considered spherical and has an important influence in the re-arrangement of the musculoskeletal system to maintain the same mechanical output (as it was found in the medio-lateral GRF induced by the abd/add hip moment).

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