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Intersegmental dynamics of the lower limb in vertical jumps †

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Abstract

The purpose of this study was to investigate changes in intersegmental dynamics of the lower limb at the instant of push-off in vertical jumps. Using a mathematical model including dynamic equations, the net joint moment (NET) was decomposed into a muscle moment (MUS), gravitational moment, and interaction moment (INT) in terms of joint acceleration and velocity. Ten subjects performed two submaximal jumps (60% and 80% of maximal height) and one maximal jump. Results showed that the hip and ankle joints mainly utilized MUS to generate NET at the push-off instant, while the knee joint primarily used INT at the instant of push-off. The hip MUS increased with increasing jump height because the deep countermovement (larger flexion angle of hip and knee joint at the push-off instant) in maximal jump was a disadvantage from intersegmental dynamics, but may be neurophysiologically advantageous.

Keywords: Biomechanics; Vertical jump; Inverse dynamics; Human movement, Human joint moment, Intersegmental dynamics

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1. Introduction

The vertical jump is very important in sports. A high vertical jump contributes to successful athletic performance, particularly in sports such as basketball, volleyball, and football. It is a crucial motor task of all human beings and requires the coordination and synchronization of multiple joints and muscles. Previous studies have emphasized the importance of the coordination of segmental actions [1-3] and the function of biarticular muscles [3-5] for enhanced jump performance.

In a vertical jump, there are two ways to propel the body's center of mass (CM) upward: a countermovement jump (CMJ) and a so-called squat jump (SJ). In a CMJ, people start from an upright position and initiate downward movement before starting to move upward, while in a SJ they start from a squatted (or semisquatted) position without a preparatory countermovement. It is well known that CMJs are generally 2-4 cm higher than SJs as a result of the stored elastic energy [6], stretch reflexes [7], and the active states of the muscles [8].

The initial instant of push-off during a CMJ (i.e., the onset of the ascent motion immediately after the descent motion) has been considered an important moment in a vertical jump because greater joint moments [8] and greater countermovement amplitudes [9] at this instant are closely associated with greater jump heights. Although these results have been primarily explained using neuromuscular characteristics such as stored elastic energy and stretch reflexes [7, 10, 11], they could be also accounted for using mechanical characteristics (e.g., intersegmental dynamics), as reported in studies of other fundamental motor skills [12-14].

Mechanically intersegmental dynamics are inevitable, since the human body is configured as a kinematic chain. Normally, the acceleration and velocity of one segment are not only associated with that segment itself but also influence the motions of other segments due to joint forces between the segments. Thus, in addition to joint moments, motion-dependent moments are important in generating segmental rotations. These motion-dependent moments are considered to be interaction moments, which can be either assistive or resistive to the goal-directed movement, depending on the chain configuration and the direction of joint acceleration [12-14]. For this reason, understanding the characteristics of intersegmental dynamics and efficiently utilizing interaction moments are very important in the control and improvement of jump performance [15].

In this study, we used a mathematical model of a four-segment linkage with respect to a local coordinate system. The net joint moment (the product of inertia and acceleration) was decomposed into a muscle moment (computed from the equations of inverse dynamics), a gravitational moment (due to gravity), and an interaction moment (caused by other joints' accelerations and velocities; e.g., the coupling inertia or Corolis force effects) [16, 17]. The purpose of this study was to investigate changes in the intersegmental dynamics of the

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lower limb at the instant of push-off according to jump height. Joint kinematics and the kinetics of submaximal and maximal jumps were examined with the four-segment linkage mathematical model. It is hypothesized that INT increases at all three joints with increasing jumping heights because people would efficiently utilize INT created by other segments' rotations in maximal jump.

2. Methods

2.1 Subjects

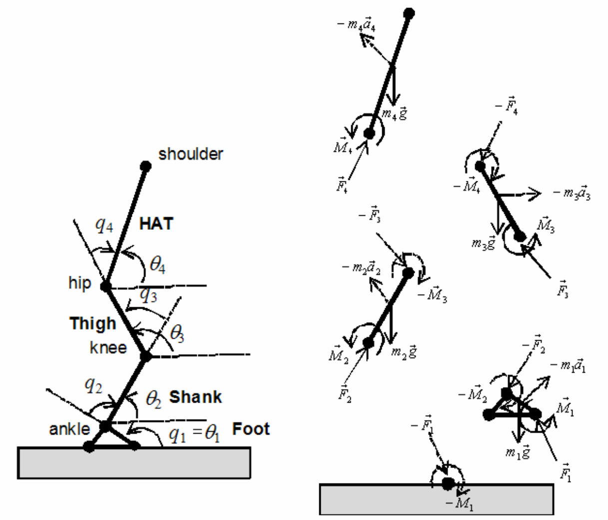
Ten male adults (age, 25.3 ± 4.0; height, 173.9 ± 4.1 cm; body weight, 746.8 ± 49.0 N) participated in this study. All subjects had been injury-free for three months prior to the study and had no problems associated with repeated maximal jumps. Prior to participation, all participants signed the informed consent form that had been approved by the institutional review board of our university.

2.2 Experimental procedures

Prior to the tests, the subjects performed a standard warm-up routine, consisting of stretching and moderate jumping. After sufficient warm-up, the subjects performed five CMJs from an upright standing position (akimbo posture) at maximal intensity. During the maximal vertical jumps, the subjects were asked to remember their kinesthetic feeling of maximal intensity. Then, they were asked perform submaximal jumps at the different levels of 25%, 50%, and 75% of the maximal height according to their kinesthetic feelings of submaximal intensities. The order of the levels of submaximal jumps was randomly selected and five trials for each submaximal condition were executed. There was no external feedback or external focus that would allow the subjects to guess or determine the jump height. The actual heights of submaximal jumps were significantly higher than the stated goals: 59.4% (*SD* = 7.7) instead of 25%, 78.1% (*SD* = 5.0) instead of 50%, and 87.5% (*SD* = 4.3) instead of 75%. We selected the trials closest to 60% (60.9%, *SD* = 2.6) and 80% (80.4%, *SD* = 1.4) of the maximal height for further analyses.

2.3 Data collection

We used a four-segment linkage model in two-dimensional space. The four segments were as follows: head-arm-trunk (HAT), thigh, shank, and foot. To construct the model, reflective markers were placed on the acromion process, greater trochanter, lateral condyle, lateral malleolus, calcaneus, and the fifth metatarsophalangeal joint. During the countermovement and propulsive phases, marker position data were obtained by a high-speed motion capture system (Hawk® Digital Real Time System, Motion Analysis System, Santa Rosa, CA, USA) at a sampling rate of 200 Hz. In addition, the ground reaction force (GRF) and center of pressure were collected by a forceplate (MP4060®, Bertec Corporation, Columbus, OH, USA) with a sampling rate of 2,000 Hz.



(a) (b)

Fig. 1. (a) Anatomical landmarks and angle definitions; (b) Free body diagrams for inverse dynamics. Note: HAT: head-arm-trunk, θ_i: segment angle relative to the positive horizontal, and q_i: joint angle relative to the distal segment ($q_i = \theta_i - \theta_{i-1}$, $i > 1$).

2.4 Model of intersegmental dynamics of the lower limb

2.4.1 Kinematic variables

Prior to any data analysis, the three-dimensional trajectories of the six reflective markers were filtered with a dual-pass 2nd order Butterworth filter (cutoff frequency of 6 Hz) and the GRF were filtered with a same filter (cutoff frequency of 20 Hz). Jump heights were calculated using the airborne time obtained from a forceplate [18]. For the joint kinematics and kinetics, two different angles such as segment angle and joint angle were used. The absolute vector angle with respect to the positive horizontal was calculated as the segment angle. The joint angle was calculated by the proximal segment angle with respect to the distal segment (Fig. 1(a)). Time derivatives of joint angles (i.e., angular velocities and angular accelerations) were numerically obtained. According to Kreighbaum & Barthel's notation [19], the extension of joint motion and plantar flexion of the ankle were expressed in positive values in reporting joint kinematic and kinetic results.

2.4.2 Kinetic equations

In order to observe the joint moment at each joint, conventional inverse dynamics [20], presented in terms of Newton-Euler equations with respect to the global reference frame, were performed with measured kinematic data and body segment parameters [21]. For the foot, shank, and thigh (i = 1, 2, and 3):

$$F_i - F_{i+1} + m_i\vec{g} = m_i\vec{a}_i$$
$$\vec{M}_i - \vec{M}_{i+1} + [\vec{r}_{d_i} \times \vec{F}_i] + [\vec{r}_{p_i} \times (-\vec{F}_{i+1})] = I_i\vec{\alpha}_i \,. \quad (1)$$

For the HAT (i = 4):

$$F_4 + m_4\vec{g} = m_4\vec{a}_4$$
$$\vec{M}_4 + [\vec{r}_{d_4} \times \vec{F}_4] = I_4\vec{\alpha}_4 \ . \qquad (2)$$

These equations can be rewritten in matrix form by eliminating joint forces as follows [22-24] (where $\vec{M}_1 = M_1 \cdot \hat{k}_1$, $\vec{M}_2 = M_2 \cdot \hat{k}_2$, $\vec{M}_3 = M_3 \cdot \hat{k}_3$, and $\vec{M}_4 = M_4 \cdot \hat{k}_4$):

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{12} & m_{22} & m_{23} & m_{24} \\ m_{13} & m_{23} & m_{33} & m_{34} \\ m_{14} & m_{24} & m_{34} & m_{44} \end{bmatrix} \cdot \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \\ \ddot{\theta}_4 \end{bmatrix} = \begin{bmatrix} M_1 - M_2 \\ M_2 - M_3 \\ M_3 - M_4 \\ M_4 \end{bmatrix} + \begin{bmatrix} G_1 \\ G_2 \\ G_3 \\ G_4 \end{bmatrix} - \begin{bmatrix} 0 & N_{12} & N_{13} & N_{14} \\ -N_{12} & 0 & N_{23} & N_{24} \\ -N_{13} & -N_{23} & 0 & N_{34} \\ -N_{14} & -N_{24} & -N_{34} & 0 \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1^2 \\ \dot{\theta}_2^2 \\ \dot{\theta}_3^2 \\ \dot{\theta}_4^2 \end{bmatrix} \qquad (3)$$

where θ_1(foot angle) = q_1, θ_2(shank angle) = $q_1 + q_2$, θ_3(shank angle) = $q_1 + q_2 + q_3$, and θ_4(HAT angle)= $q_1 + q_2 + q_3 + q_4$. The dynamic equations of the four-segment linkage were rephrased with respect to local coordinate system (i.e., joint angle) and the net joint torque was partitioned as follows in order to determine the physical meanings of the various sources contributing to net joint moments:

$$NET_i = MUS_i + GRA_i + INT_i \qquad (4)$$

where NET_i is the net joint moment, MUS_i is the muscle moment, GRA_i is the gravitational moment, and INT_i is the interaction moment.

Then,

$$NET_i = (\sum_{j=i}^{4} m_{jj} + 2\sum_{j=i+1}^{4} m_{ij} + 2\sum_{j=i+2}^{4} m_{i+1j})\ddot{q}_i \qquad (5)$$

$$MUS_i = M_i \qquad (6)$$

$$GRA_i = g\sum_{j=i}^{4} r_j \cos(q_j) \qquad (7)$$

and INT_i is the other terms consisting of $\dot{q}_j^2$, $\ddot{q}_j$ (j=1 to 4 except i), and $\dot{q}_i\dot{q}_j$ at each joint.

2.5 Statistical analysis

One-way repeated measures analysis of variance (ANOVA) was performed to assess the effects of jump height on NET, MUS, INT, GRA, and kinematic data. The measured jump levels were 60%, 80%, and 100% of the maximal height. A familywise statistical significance level was set at 0.05. When sphericity assumption was violated, the Huynh-Feldt adjustment for degrees of freedom was applied. When a significant main effect was detected, the post hoc test (Bonferroni's multiple comparisons) was used to identify the cause of significance.

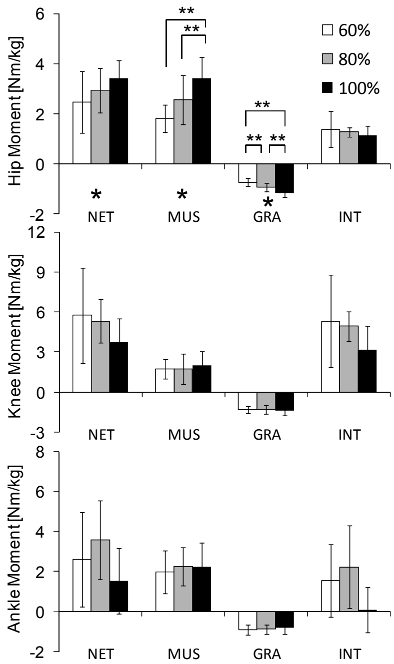


Fig. 2. Intersegmental dynamics of the lower limb at the push-off instant in vertical jumps and their changes with increases in jump height. Error bar indicates a standard deviation.* indicates a main effect of jump height (p<0.05). ** indicates significant mean difference between two levels (p<0.017). Positive values are extension moments and negative ones are flexion moments.

3. Results

3.1 Intersegmental dynamics of the lower limb at the push-off instant

Fig. 2 presents changes in intersegmental dynamics of the lower limb at the push-off instant across three different jump heights. Positive values were extension moments and negative ones were flexion moments. The patterns in generating NET were different at each joint. The hip NET was primarily created by MUS, while the knee NET was mainly generated by INT. All GRAs worked as flexion moment. In addition, increased jump height changed the decomposition. The hip MUS increased with increasing jump height ($p<0.05$). Post hoc test revealed that the mean hip MUS at maximal jump was significantly higher than the other two submaximal jumps. Also, the hip flexion GRA continuously increased flexion moments with increasing jump height ($p<0.05$). The detailed changes within INT are presented in the following section.

3.2 The contribution of coupling inertia to INT at the push-off instant

Since the angular velocities ($\dot{q}_i$) were close to zero at the push-off instant, centrifugal force-driven ($\dot{q}_i^2$) and Coriolis force-driven ($\dot{q}_i\dot{q}_j$) INTs were near zero. Therefore, coupling inertia (the off-diagonal element in an inertia coefficient matrix) was a dominant source of the INT at each joint.

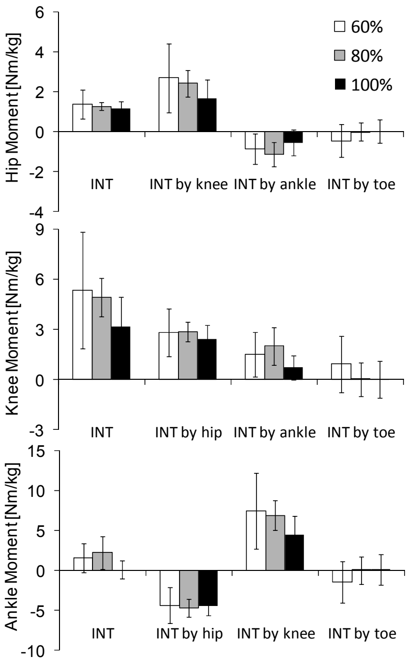


Fig. 3. Contribution of coupling inertia effect to INT at the push-off instant and their variations according to jump height. Error bar indicates a standard deviation. Positive values are extension moments and negative ones are flexion moments.

Fig. 3 shows the contribution of coupling inertia effect to INT at the push-off instant and its variations with jump height. The hip INT was dominantly attributed to the coupling inertia effect of the knee joint (INT by knee). The ankle INT was assisted by the coupling inertia effect of the knee joint (INT by knee) but mainly cancelled out by the coupling inertia effect of the hip joint (INT by hip). At the knee joint, the coupling inertia effects of both the hip and ankle joints contributed to knee INT positively. Thus, the results demonstrated that INT caused by the coupling inertia effect of the adjacent joint was assistive, while INT induced by the coupling inertia effect of the non-contacting joint was resistive at each joint. The coupling inertia effect of the toe joint (INT by toe) was trivial to each joint. There was no significant effect of jump height on the contribution of coupling inertia to INT.

3.3 Flexion angles at the push-off instant

Table 1 shows the mean values of the flexion angles at the push-off instant. Flexion angles significantly increased with increased jump height, except for the ankle joint ($p<0.05$). The flexion angle of the ankle joint did not vary with jump height.

4. Discussion

In order to investigate the intersegmental dynamics of vertical jumping at the push-off instant, this study decomposed NET into three contributing sources using a mathematical model. The three sources were MUS computed with inverse dynamics, GRA due to a gravity, and INT caused by the acceleration and velocities of other joints.

The push-off instant in a CMJ is very important in jump performance because an explosive GRF, created by the contributions of three joint motions, is necessary for maximal jump height and controlled GRF are also required for submaximal jumps. The current study indirectly indicated that the most positive contribution to the ground reaction force in response to increased jump height was hip MUS, because only hip MUS significantly increased with increasing jump height. This finding is in good accordance with the finding of Vanrenterghem et al. [9], who showed that the amplitude of CMJ is closely related to increases in submaximal jump heights. This was primarily attributed to the significant contribution of the most proximal joint (i.e., the hip joint).

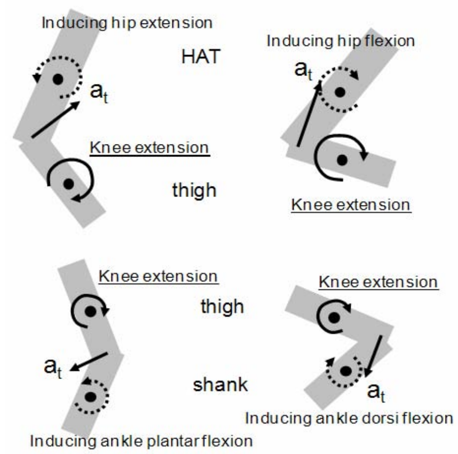
Table 1. Changes in flexion angles at the push-off instant (unit: degrees) [mean (*SD*)].

	Hip	Knee	Ankle
60%	69.9 (18.6)	80.4 (11.9)	111.2 (5.2)
80%	84.8 (17.2)	84.3 (10.9)	111.0 (3.7)
100%	115 (23.8)	98.8 (16.6)	111.7 (4.6)
F	51.4	19.6	0.54
P	0.001*	0.001*	0.59

* indicate a significant main effect of jump height ($p<0.05$).

At the push-off instant, the contributions of the decomposed moments to NET were different by joint. The hip and ankle mainly generated NET with the help of MUS, while the knee predominantly used INT. This difference might be attributed to the location of each joint in a multijoint system. The hip joint is the most proximal joint and must overcome the largest inertia (HAT) in order to lift the body CM upward, requiring the active contribution of MUS (Fig. 2). The knee joint, as a middle joint, may work as a subordinate joint because the hip joint is the leading joint and provides the dynamic foundation of the system at the push-off instant. However, the knee joint might work as a leading joint in the middle of the propulsive phase when the leading role of the hip joint subsides [25]. Then, the optimal solution of a proximal-to-distal sequence of segmental rotation would be naturally achieved [1, 3].

The intersegmental dynamics of the lower limb changed according to jump height. The hip joint showed significantly increased MUS in order to overcome the increased flexion GRA. The knee and ankle INTs changed but showed no significant change due to large standard deviations. These large standard deviations might be partially attributed to individual differences and partially attributed to data processing (e.g., fluctuated angular acceleration due to second time derivatives at knee and ankle joints). The INT at each joint was mainly attributed to the coupling inertia effect of the next adjacent joint (Fig. 3). Since no effect of jump height on INT was detected, our hypothesis was not supported. These results were partially explained by the chain configuration of a multijoint system.



(a) (b)

Fig. 4. Illustration on the relationship with the chain configuration and the coupling inertia effect of the knee joint motion at the push-off instant: (a) Configuration of a segment chain in submaximal jump; (b) and in maximal jump. Note: a_t = tangential acceleration acting on the adjacent segment.

Fig. 4 shows the relationship between chain configuration and the coupling inertia effect at the push-off instant. Normally the INT at each joint is affected by coupling inertia effects (angular acceleration of the other joints), centrifugal force effects (squared angular velocity of the other joints), and Coriolis force effects (the product of two different joint angular velocities). However, the coupling inertia effects might be the unique source of INT at the push-off instant. Because all angular velocity at this moment is near zero, only tangential force-drive INT is effective. In submaximal jumps, the subjects tended to have small amplitudes of flexion angles (less than 90° for the hip and knee) at the push-off instant (Table 1 and Fig. 4(a)). The tangential acceleration created by knee extension assisted the other segment motions (i.e., the hip extension and ankle plantar flexion). However, when the subjects flexed deeply at the push-off instant (more than 90° for the hip and knee) to maximize their jump heights, the tangential accelerations created by knee extension tended to produce reverse effects on the other segment motions (i.e., the hip flexion and ankle dorsiflexion) (Fig. 4(b)). Therefore, the hip INT and ankle INT created by coupling inertia effects of the knee were reduced with increases in jump height. This reduced hip INT might trigger more activation of hip MUS because the reduced INT hinders the upward body CM motion.

The larger countermovement at the push-off instant does not provide people with advantages from the perspective of intersegmental dynamics. However, these configuration may trigger increased extension MUS contributions as a result of increased stored elastic energy or/and stretch reflexes [6-8, 10, 11].

5. Conclusions

This study decomposed net joint moments into a muscle moment, gravitational moment, and interaction moment using closed forms of dynamic equations. We investigated intersegmental dynamics of the lower limb at the push-off instant in vertical jumps. Each joint showed different NET generating patterns. As the jump height increased, deeper countermovement was detected. The increased amplitude of the countermovement was not advantageous from the perspective of intersegmental dynamics. Rather this change might trigger increased extension MUS activities, resulting in neurophysiological advantages.

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Nomenclature

The number of subscripts is used in such a manner that a segment and its distal joint have the same numbers (i=1: foot or toe, 2: shank or ankle, 3: thigh or knee, 4: HAT or hip), where HAT means head, arms, and trunk segments together.

$\hat{i}_i, \hat{j}_i, \hat{k}_i$: Unit vector of local coordinate system affixed to a segment

$q_i, \dot{q}_i, \ddot{q}_i$: Joint angle, angular velocity, angular acceleration with respect to the distal segment

$\theta_i, \dot{\theta}_i, \ddot{\theta}_i$: Segment angle, angular velocity, and angular acceleration with respect to the positive horizontal

l_i, ρ_i : Length of a segment and the distance from the distal joint to the center of mass of a segment

g : Gravitational constant

m_i, I_i : Mass of a segment and moment of inertia at the center of mass of a segment

$\vec{a}_i, \vec{\alpha}_i$: Linear and angualar acceleration at the center of mass of a segment

$\vec{M}_i, \vec{F}_i$: Resultant joint moment and resultant joint force

$\vec{r}_{p_i}, \vec{r}_{d_i}$: Vector from the center of a segment to the proximal joint and the distal joint

m_{ij}, N_{ij} : Element of inertia coefficient matrix and element of coefficient of interaction moment matrix.

These are formed using indices j = 1, 2, 3, h = 1, 2, 3, 4 and k = 1, 2, 3, 4,

$\mu_j = l_j \sum_{i=j+1}^{4} m_i$, $\mu_4 = 0$, $\delta_h = \mu_h + \dfrac{I_h + m_h \rho_h^2}{l_h}$, $\gamma_h = \mu_h + m_h \rho_h$, $M_{hh} = l_h \delta_h$, $M_{hk} = l_h \gamma_k c_{hk}$, $M_{kh} = M_{hk}$, $N_{hh} = 0$, $N_{hk} = l_h \gamma_k s_{hk}$, $N_{kh} = -N_{hk}$, where $c_{hk} \equiv \cos(q_h - q_k)$ and $s_{hk} \equiv \sin(q_h - q_k)$ for the element ($k > h$).

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