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The Maximal and Submaximal Vertical Jump: Implications for Strength and Conditioning

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Abstract. Lees, A., J. Vanrenterghem, and D. De Clercq. The maximal and submaximal vertical jump: implications for strength and conditioning. *J. Strength Cond. Res. 18(4):787–791. 2004.*—The vertical jump is a widely used activity to develop explosive strength, particularly in plyometric and maximal power training programs. It is a multijoint action that requires substantial muscular effort from primarily the ankle, knee, and hip joints. It is not known if submaximal performances of a vertical jump have a proportional or differential training effect on the major lower-limb muscles compared to maximal jump performance. Therefore, the purpose of this study was to investigate the contribution that each of the major lower-limb joints makes to vertical jump performance as jump height increases and to comment on the previously mentioned uncertainty. Adult males ($N = 20$) were asked to perform a series of submaximal (LOW and HIGH) and maximal (MAX) vertical jumps while using an arm swing. Force, motion, and electromyographical data were recorded during each performance and used to compute a range of kinematic and kinetic data, including ankle, knee, and hip joint torques, powers, and work done. It was found that the contribution to jump height made by the ankle and knee joints remains largely unchanged as jump height increases (work done at the ankle: LOW =1.80, HIGH = 1.97, MAX = 2.06 J·kg^{-1}, $F = 3.596$, $p = 0.034$; knee: LOW = 1.62, HIGH = 1.77, MAX = 1.94 J·kg^{-1}, $F = 1.492$, $p = 0.234$) and that superior performance in the vertical jump is achieved by a greater effort of the hip extensor muscles (work done at the hip: LOW = 1.03, HIGH = 1.84, MAX = 3.24 J·kg^{-1}, $F = 110.143$, $p < 0.001$). It was concluded that the role of submaximal and maximal jumps can be differentiated in terms of their effect on ankle, knee, and hip joint muscles and may be of some importance to training regimens in which these muscles need to be differentially trained.

Key Words. biomechanics, joint kinetics, strength training

Introduction

The vertical jump is a widely used activity within strength and conditioning programs to develop explosive strength, particularly in lower-limb plyometric programs and in maximal power training. In these programs, participants may be required to undertake several repetitions and several sets of a vertical jump movement. When multiple repetitions of an activity are performed, it is likely that each performance will be submaximal, and the training effect of these submaximal performances may differ from that expected from maximal performances of the activity. Put the other way around, it is not known if submaximal performances of a vertical jump have a proportional or differential training effect on the major lower-limb muscles compared to maximal jump performance. In general, it is assumed that submaximal performances have a proportional effect on the lower-limb muscles, but this assumption has never been challenged. It would be of interest to strength and conditioning trainers to know how submaximal performance relates to maximal performance in this multijoint exercise, as it may be possible to optimize training by eliminating the tendency to perform submaximally if found undesirable or to utilize any benefits that submaximal performances may have as a planned part of the training program. In other words, more specific knowledge of the effect of jumping on lower-limb muscle loading would enable a more objective use of this activity for training purposes.

The vertical jump is a multijoint action that requires substantial muscular effort from the ankle, knee, and hip joints. Motion analysis provides a detailed picture of the muscular effort expended at the joints during the performance of exercises in terms of the net joint torque and power histories and work done. While there have been numerous studies investigating these biomechanical characteristics for maximal vertical jumping (2, 5), there has been no attempt to investigate the nature of muscular effort at the joints in submaximal jumping exercises. Better performance and/or more efficient training may be possible with exercises which are able to target specific muscle groups. Therefore, the purpose of this study was to investigate the contribution that each of the major lower-limb joints makes to submaximal and maximal performance in the vertical jump and to comment on the assumption that in submaximal performance there is a proportionally reduced contribution from the lower-limb joints compared to maximal jump performance.

Methods

Experimental Approach to the Problem

In order to investigate the contribution that each lower-limb joint makes to the vertical jump, a progressive performance paradigm was used. This required participants to jump at a given submaximal height (termed LOW), then again at a greater height (termed HIGH), and then finally for maximal height (termed MAX). Twenty athletic adult males (mean ± standard deviation [*SD*]: age = 19.9 ± 3.9 years; height = 180.0 ± 6.5 cm; mass = 75.4 ± 13.3 kg) participated in this investigation. All the participants were competitively active in sports that ranged from field games play to gymnastics. All were fit and injury free, and each gave informed consent as required by the University Ethics Committee.

Data Collection

Participants were given the opportunity to warm up with light exercise and stretching and to practice the 3 types of jump. They were required to perform 3 repetitions of each condition using a natural jumping technique that includes the use of an arm swing. Participants performed each jump on a force platform (Kistler, Winterthur, Switzerland). Reflective markers were placed over the second metatarsal-phalangeal joint; lateral malleolis; lateral knee, hip, wrist, and elbow joints; acromion process; C7; and on the vertex of the head using a marker placed on the top of a cap worn on the head. The 3-dimensional (3D) position of each marker was recorded using a 6-camera optoelectronic motion capture system (Proreflex, Qualysis, Savedalen, Sweden). Electromyographical (EMG) recordings (TEL100, Bio Pac Systems, Goleta, CA) were made from the rectus femoris, vastus lateralis, biceps femoris, and gastrocnemius muscles. After degreasing the skin and lightly abrading to reduce skin resistance to below 5,000 ohms, electrodes were placed 20 mm apart on the center of each muscle (3). Earth electrodes (to provide an electrical reference zero) were placed on the bony prominences of the tibia and superior iliac crest as appropriate. Data were collected for a period of 6 seconds, which allowed approximately 2 seconds of quiet standing before the jump commenced. The motion data were collected at 240 Hz, while the force and EMG data were collected at 960 Hz. All data were electronically synchronized in time.

Data Reduction

Kinematic Analysis Procedures. The 3D motion data from the 16 markers were used to define a 12-segment biomechanical model using segmental data proposed by Dempster (4) for adult males. These data were used to calculate the segment and whole-body center of mass (CM) locations. As vertical jumping is essentially a sagittal plane activity, data were projected onto the sagittal plane in order to compute segment orientations and joint flexion angles. All kinematic data were then smoothed using a Butterworth fourth-order zero-lag filter with padded end points (9) and a cutoff frequency of 7 Hz based on a residual analysis and qualitative evaluation of the data. Derivatives were calculated by simple differentiation (11).

Kinetic Analysis Procedures. The force data were averaged over 4 adjacent points so that each force value corresponded to each motion data value at 240 Hz. Inverse dynamics using standard procedures (7, 11) was used to compute the segment proximal and distal net joint reaction components and the net joint torques at the ankle, knee, and hip. Joint power (the product of net joint torque and joint angular velocity) and work done (the time integral of the power production at a joint between specified time points) were calculated based on standard procedures (6). Extension joint torques are presented as positive, while flexion joint torques are negative. Similarly, joint power generation is presented as positive, while joint power absorption is negative. For all joint variables, the sum of the left and right limbs was computed. All kinetic variables were normalized to body mass in order to reduce the influence of body mass on the values computed. Data are presented over the period from the start of the movement to takeoff. The resulting data set defined the movement time of the action, which was isolated and normalized to 100 points by linear interpolation.

EMG Analysis Procedures. The raw EMG signal was high-pass filtered (8) at 10 Hz and low-pass filtered (11) at 350 Hz using Butterworth fourth-order zero-lag filters with padded end points. The data were then rectified and further smoothed using a 10-Hz low-pass Butterworth fourth-order zero-lag filter. EMG data were evaluated qualitatively.

Statistical Analyses

A 1-way ANOVA with Tukey test was used for establishing differences between jump height conditions, and a value of $p < 0.05$ was used to indicate statistical significance. The effect size (10) is reported by omega squared (ω^2) and the power also reported where nonsignificant differences are found.

Results

As jumps increased in performance from LOW through HIGH to MAX, the jump height, as determined by the height raised by the CM relative to its standing position, increased significantly (LOW = 0.35 ± 0.03 m; HIGH = 0.44 ± 0.03 m; MAX = 0.53 ± 0.04 m; $p \leq 0.01$) with the LOW and HIGH performances being 65 and 83% of MAX, respectively. The greater jump height was associated with a greater depth of countermovement (LOW = −0.17 ± 0.02 m; HIGH = −0.22 ± 0.04 m; MAX = −0.30 ± 0.06 m; $p \leq 0.001$), greater forward inclination of the trunk during the countermovement (LOW = 14.4 ± 7.1°; HIGH = 25.8 ± 7.2°; MAX = 44.8 ± 9.5°; $p \leq 0.001$), and a greater movement time (LOW = 0.73 ± 0.10 s; HIGH = 0.81 ± 0.13 s; MAX = 0.96 ± 0.14 s; $p \leq 0.001$).

The joint torques at the ankle, knee, and hip (Figure 1) reflect the high joint torques generated toward the later part of the movement (70–100%) in order to perform the ascent (i.e., joint extension phase). In these graphs it can be seen that the ankle joint torques all have similar peak values that occur at around 90% of the movement, just before takeoff. The knee joint torques (Figure 1 middle) show an unexpected reduction in peak value as jump height increases, while in contrast the hip (Figure 1 lower) shows a marked increase in peak value as jump height increases.

The work done at each joint is computed from the integral of the positive power during the ascent. These values are given in Figure 2, and it can be seen that as jump height increases, the work done by the hip increases markedly (LOW = 1.03, HIGH = 1.84, MAX = 3.24 $J \cdot kg^{-1}$, $F = 110.143$, $p \leq 0.001$, $\omega^2 = 0.79$), the work done by the ankle increases slightly (LOW = 1.80, HIGH = 1.97, MAX = 2.06 $J \cdot kg^{-1}$, $F = 3.596$, $p = 0.034$, $\omega^2 = 0.11$) with a moderate effect size (10), but the work done by the knee does not change significantly (LOW = 1.62, HIGH = 1.77, MAX = 1.94 $J \cdot kg^{-1}$, $F = 1.492$, $p = 0.234$, $\omega^2 = 0.05$, power = 0.63) even though the power of the test is moderate (10).

The electrical activity in selected muscles is illustrated in the EMG data of Figure 3. A qualitative inspection of these graphs shows one major difference between conditions, namely, the earlier peak for the MAX condition in the biceps femoris muscle (Figure 3d). This earlier muscle activity is associated with an earlier onset of muscle force that will serve to increase the hip extension torque while at the same time reduce the knee torque. This earlier activity is probably a result of the greater angle of forward inclination of the trunk. A second difference worth noting is the earlier reduction from maximal activity in the MAX and HIGH conditions compared to the LOW condition in both the vastus lateralis and the rectus femoris (Figure 3b,c). This would serve to reduce the knee extensor torque during the latter part of the propulsion phase. Thus, the lower knee torque in the MAX condition compared to the LOW condition (as noted in Figure 1) may be due to increased biceps femoris torque in the earlier part of the propulsion phase and reduced quadriceps torque in the later propulsion phase.

DISCUSSION

A progressive performance paradigm was used in order to evaluate the contribution of the individual lower-limb joints to jump height as jump height increased to a maximum value. It has been shown that the effort made at the ankle and knee joints increases only slightly as jump height increases and that progression from submaximal to maximal performance in the vertical jump is achieved through the greater effort produced by the hip joint extensor muscles in order to generate higher torques, power outputs, and work done at the hip. The assumption that the effort expended around each joint increases proportionally as performance in the vertical jump increases is not supported. The data suggest that as performance progresses toward maximal, it is the hip joint extensor muscle activity that increases to achieve this, while the muscular effort at the ankle and knee remain relatively unchanged.

Before interpreting this finding with regard to strength and conditioning training, it is necessary to comment on some biomechanical aspects of vertical jump performance. The power delivered by the ankle and knee joints occurs in the very last part (90–100%) of the movement time. This power is determined by the net joint torque produced by muscles and by the angular velocity of the joint. The net joint torque is determined by the combination of muscle forces acting around the joint and is influenced by the action of biarticular muscles. For the ankle joint, it has been shown that the power delivered by the ankle joint comes from 3 sources (1): muscle contraction (27%), return of previously stored energy in the muscle tendon unit (53%), and power transferred from the knee joint through biarticular muscle action (20%). This latter mechanism is of interest because this enables the ankle joint to deliver more power than is possible from just the ankle joint muscles alone. It comes about because the biarticular muscle (gastrocnemius) is required to lengthen as the knee joint extends. If the length of this muscle is kept constant, then knee extension will also cause ankle plantar flexion, enabling effort at the knee to be transferred to effort at the ankle. The ankle joint torque, work done, and EMG intensity of the gastrocnemius muscle are all similar for each jump height, suggesting that the ankle joint muscles operate in a similar way as jump height increases.

The same possibility of power transfer exists for the knee joint, although the nature of muscle action is more complex. The net joint torque at the knee is influenced positively by the action of the vasti muscle group and the rectus femoris, the latter being a biarticular muscle that has the capability of transferring power from the hip joint to the knee as the hip extends in the same way as described previously for the gastrocnemius. Acting against this is the muscle force of the hamstrings and gastrocnemius. The reduction of joint torque at the knee as jump height increases (Figure 1b) may be due to both a reduced torque from the knee extensor muscles and an increased torque from the knee flexor muscles, as suggested previously based on the EMG evidence. The knee flexor torque

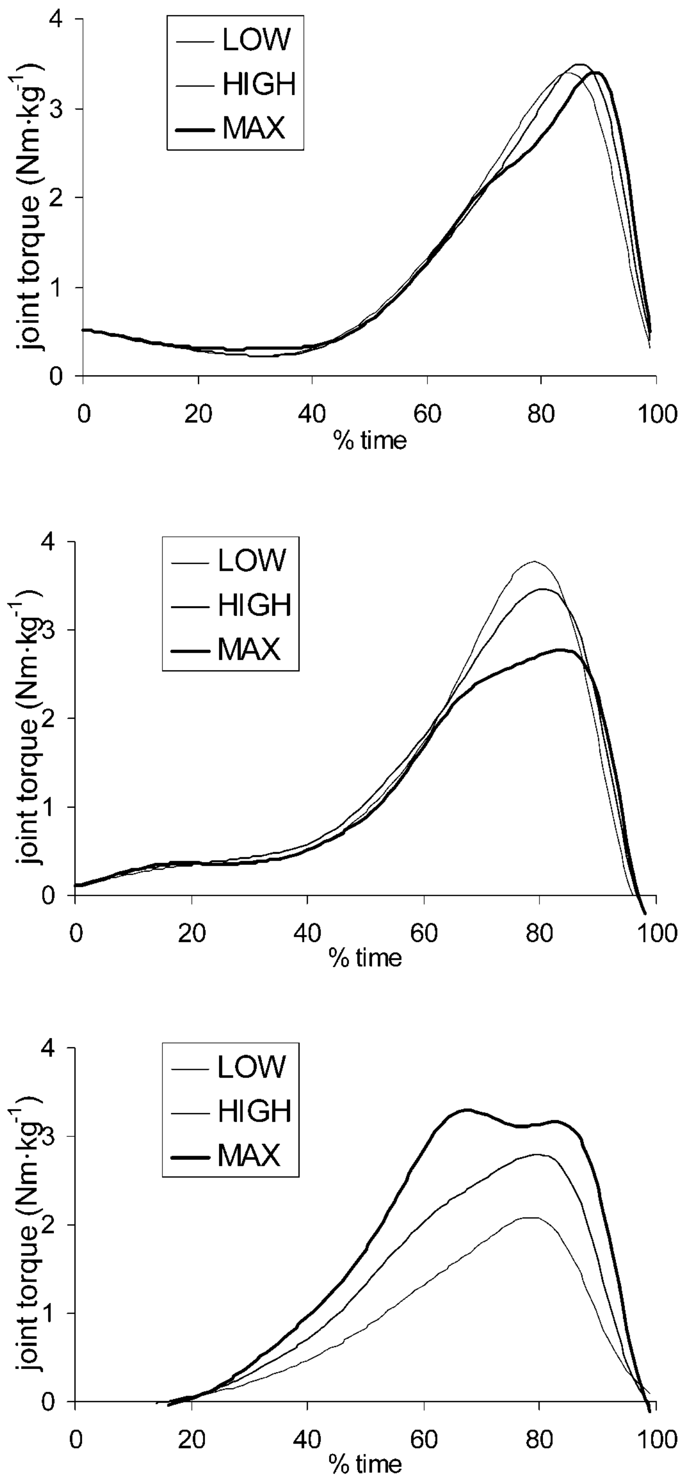

Figure 1. Typical time-normalized graphs for the 3 jump types for joint torque (top) ankle, (center) knee, and (bottom) hip.

is unlikely to be influenced by the action of the gastrocnemius, as it has been argued here that the muscle force associated with this muscle changes little over the different jump heights, so the hamstrings (as reflected in the EMG signal of the biceps femoris; Figure 3) are likely to be the main cause of this reduced net knee joint torque. This earlier activation of the hamstrings would be consistent with the need for an earlier extension of the trunk

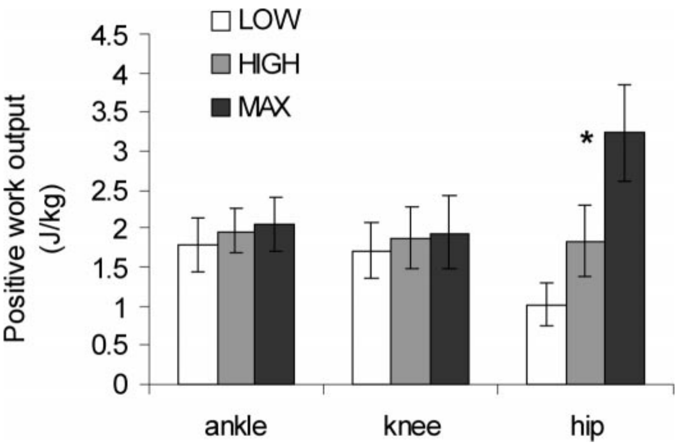

FIGURE 2. Positive work output in each joint for the 3 jump types (* indicates significant difference between jump conditions).

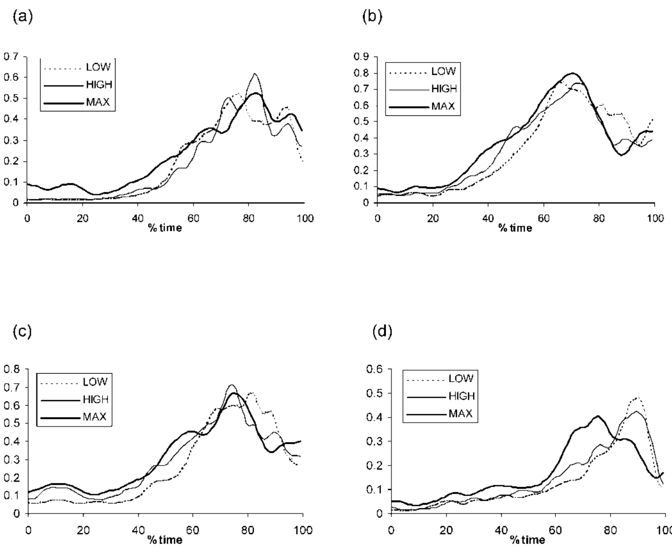

FIGURE 3. Typical time normalized graphs for the 3 jump types for muscle EMG for (a) gastrocnemius, (b) vastus lateralis, (c) rectus femoris, and (d) biceps femoris.

due to its greater forward lean in the maximal jumping condition. It has been noted previously that there is a possibility that the knee extensors reduce their level of activity earlier in the MAX compared to the LOW jump, but the levels of maximal activation do not differ. This would affect the pattern of net joint torque, but it would not reduce the maximal effort produced by the knee extensors; that is, they continue to operate at a similar level as jump height increases. Evidence to support this view also comes from the work done at the knee, which does not change significantly. The hip joint shows a marked increase in the work done as jump height increases, and although there are no EMG data to support the role of the hip extensors other than the biarticular biceps femoris, which shows an increase in the maximal jump condition, it is likely that the increase in jump height is determined by the increased activity of hip extensor muscles, while the effort from the knee and ankle extensor muscles remains largely unchanged.

These findings have implications for strength and conditioning training. The first is that the hip joint extensors work maximally only in maximal vertical jumps and specifically when there is an opportunity to extend the trunk from a forward inclined position. This may not happen in power training, for example, when a vertical jump is performed with a loaded bar across the shoulders. When a bar is used in this way, the trunk tends to be held more upright, and this prevents the hip extensor muscles from being used maximally. It may be better to use alternative methods of loading, such as a weighted vest or belt, which may not limit the range of motion at the hip to the same degree.

A second implication is that the effort at the ankle and knee joints appears to be maximal in submaximal jumps. If the focus of training is to develop ankle and knee joint muscles, then the jump could be performed submaximally while still achieving maximal activation of the ankle and knee joint muscles. This finding would also have significance for power training in which repeated jumps with additional loads are used. It is likely that the additional load would increase joint torques and power outputs, but maximal values for the ankle and knee muscles could be reached using lower jump heights. This may in turn enable greater volumes of training to be undertaken.

In summary, the findings of this study help clarify the role of lower-limb joint function in the performance of the vertical jump. The role of submaximal and maximal jumps can be differentiated in terms of their effect on ankle, knee, and hip joint muscles and may be of some importance to training regimens in which these muscles need to be differentially trained. Submaximal jumps appear to stress the ankle and knee muscles as adequately as maximal jumps. Maximal jumps are achieved through the greater engagement of the hip extensor muscles.

PRACTICAL APPLICATIONS

When using a vertical jump type of movement in training, high levels of effort are required by the ankle and knee muscles when using only moderate (i.e., over 60% of maximal) height jumps. Thus, if a training regimen is designed to train these muscle groups, submaximal jumping is a sufficient stimulus. However, if the training regimen is targeted at the hip extensor muscles, then only maximal jumping will stimulate maximal activity in these muscles. When additional loads are used for power training, the loads should be carried in a way that enables forward inclination of the trunk. A weighted vest or belt may be more appropriate than a bar held across the shoulders. If the trunk inclination is prevented, the full engagement of the hip extensor muscles will be limited with a consequential reduced training effect in these muscles.

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