Enhanced Performance With Elastic Resistance During the Eccentric Phase of a Countermovement Jump

Saied Jalal Aboodarda, Ashril Yusof, N.A. Abu Osman, Martin W. Thompson, and A. Halim Mokhtar

**Purpose:** To identify the effect of additional elastic force on the kinetic and kinematic characteristics, as well as the magnitude of leg stiffness, during the performance of accentuated countermovement jumps (CMJs).

**Methods:** Fifteen trained male subjects performed 3 types of CMJ including free CMJ (FCMJ; ie, body weight), ACMJ-20, and ACMJ-30 (ie, accentuated eccentric CMJ with downward tensile force equivalent to 20% and 30% body mass, respectively). A force platform synchronized with 6 high-speed infrared cameras was used to measure vertical ground-reaction force (VGRF) and displacement. **Results:** Using downward tensile force during the lowering phase of a CMJ and releasing the bands at the start of the concentric phase increased maximal concentric VGRF (6.34%), power output (23.21%), net impulse (16.65%), and jump height (9.52%) in ACMJ-30 compared with FCMJ (all \(P < .05\)). However, no significant difference was observed in the magnitude of leg stiffness between the 3 modes of jump. The results indicate that using downward recoil force of the elastic material during the eccentric phase of a CMJ could be an effective method to enhance jump performance by applying a greater eccentric loading on the parallel and series elastic components coupled with the release of stored elastic energy. **Conclusions:** The importance of this finding is related to the proposition that power output, net impulse, takeoff velocity, and jump height are the key parameters for successful athletic performance, and any training method that improves impulse and power production may improve sports performance, particularly in jumping aspects of sport.

**Keywords:** elastic band, power output, stretch-shortening cycle, elastic energy

Greater development of lower body power output and jump height has been shown to occur when performing a countermovement jump (CMJ) compared with a squat jump.\(^1\)\(^-\)\(^3\) This phenomenon has been attributed to the sequencing of a fast eccentric (stretching) and concentric (shortening) action of the quadriceps in the CMJ, known as the stretch-shortening cycle (SSC), that improves jumping performance through a number of myogenic and neurogenic factors.\(^4\)\(^-\)\(^6\) Immediately linked to this concept is the loading of the quadriceps muscle throughout the eccentric phase of the SSC movement, which amplifies the prestretch state of muscle and increases the subsequent force-generating capability in the concentric phase.\(^7\) Although the relative contribution of this stretch-induced gain in muscle function has not been fully elucidated as yet, the results have been attributed to the recovery of stored elastic energy in the muscle–tendon units, interaction effects of contractile components with tendinous structures, and myoelectric potentiation, as well as the stretch reflex (motoneuron pool) that is induced by greater than normal stretch of the intrafusal muscle fibers during the braking phase of the SSC.\(^6\)\(^-\)\(^8\)

In an attempt to maximize jumping performance, Sheppard et al\(^5\) used the additional load of dumbbells during the lowering phase of a CMJ and asked the subjects to release the load just before initiation of the push-off phase. This method, called accentuated CMJ, produced superior kinetic and kinematic values compared with a typical CMJ in which the load is equal in the eccentric and concentric phases. The finding was attributed to the effect of faster eccentric loading on the preparatory active state of actin-myosin cross-bridge attachment before the concentric phase. In a more recent investigation by Argus et al,\(^9\) additional elastic bands provided downward vertical tension during a CMJ; however, no improvement was observed in peak power output compared with free CMJ (FCMJ; ie, body weight only). On this basis, the effects of using the tensile force of elastic resistance on kinetic and kinematic characteristics of accentuated CMJ remain ambiguous.

Previous studies have clearly demonstrated that the spring-like movement of the lower limb muscles
(eg, jumping and running) is affected by overall active and passive stiffness of the musculoskeletal system, including muscles, tendons, and ligaments.\textsuperscript{10,11} The active stiffness of the leg muscles has been shown to be adjusted to accommodate changes in parameters such as contact time,\textsuperscript{12} running speed,\textsuperscript{13} jump height,\textsuperscript{14} and hopping frequency.\textsuperscript{11} These adjustments of leg stiffness can affect kinetic and kinematic characteristics of a CMJ. For instance, in the study by Hobara et al,\textsuperscript{12} leg stiffness can affect kinetic and kinematic characteristics of a CMJ. For instance, in the study by Hobara et al,\textsuperscript{12} leg stiffness was increased by reducing contact time, and, in return, it extended aerial flight time during successive hops. On this basis, it is of interest to investigate whether additional external load in an accentuated CMJ can change leg stiffness. The importance of this question resides in the fact that adjustment of leg stiffness may determine the subsequent change in the mechanical characteristics of a CMJ.\textsuperscript{11}

The aim of the current study therefore was to identify the effect of additional elastic force on the kinetic and kinematic characteristics, as well as the magnitude of leg stiffness, during the performance of an accentuated CMJ. The outcome of the study may lead to the development of a novel training method to enhance athletic performance in sports like volleyball and basketball and other sports with high instantaneous speed and power.

**Material and Methods**

**Subjects**

Fifteen trained male subjects participated in this study. Their age, height, and mass were 22.6 $\pm$ 5.3 years, 171.4 $\pm$ 7.7 cm, and 74.9 $\pm$ 4.1 kg, respectively. All participants had been undertaking various forms of plyometric training twice a week within the 6-month period before the experiment. The study was approved by the University of Malaya review board for research involving the use of human subjects. After explanation of the possible risks and discomfort and subsequently completion of a medical screening questionnaire, subjects gave their written informed consent. None of the participants had a history of taking medications, and there were no reports of musculoskeletal injuries or metabolic disease. Because subjects were drawn from a variety of sporting backgrounds, they were asked to continue their training protocols but refrain from vigorous physical activity for a period of 1 week before their involvement in the study, thus avoiding confounders such as fatigue and delayed-onset muscle soreness due to strenuous training programs.

**Design**

To determine the effect of using additional tensile force of elastic bands on muscle stiffness and jumping performance, subjects performed FCMJs (ie, body weight), accentuated eccentric CMJs in which elastic bands provided downward tensile force equivalent to 20% of the subject’s body mass (ACMJ-20), and ACMJs in which elastic bands provided downward tensile force equivalent to 30% of the subject’s body mass (ACMJ-30). All data were collected in 1 experimental session. Subjects were verbally encouraged to demonstrate their maximal jump height through all 3 types of CMJ. The order of the measurements was randomized across the 3 exercise conditions. All subjects wore the same type of footwear to control different shoe–sole compliance–absorption properties (Reebok Pivot II).

**Methodology**

Subjects attended a single testing session that commenced with a warm-up protocol consisting of 2 sets of 10 body-weight squats at a self-selected velocity followed by 2 sets of 5 FCMJs performed with maximal effort.\textsuperscript{9} Warm-up sets were separated by 1-minute rests. During the 10-minute recovery period, reflective spherical markers (9 mm in diameter) were fixed securely on the lateral side of the bony anatomical landmarks of the right and left legs, including the second metatarsal head, the calcaneus, the lateral malleolus, the lower lateral third of the shank, the lateral epicondyle of the femur, the upper third of the thigh, and the greater trochanter.

After the warm-up and 10-minute recovery period, vertical-jump performance was assessed for each of the 3 jumping conditions in randomized order, and subjects were encouraged to reach a maximum height in each jump. The participants performed 3 maximal CMJ trials for each condition on a force plate (Kistler Instrument Inc, Winterther, Switzerland) that had been calibrated with known loads before the testing session. The force platform was synchronized with 6 high-speed infrared cameras (Vicon MX-F20) positioned around the performance area of the jumps. To minimize the possibility of fatigue confounding the data collection, a 2-minute rest period was provided between trials.

**FCMJ**

Subjects initiated the FCMJ from a standing position and squatted to a self-selected depth of knee flexion and immediately jumped for maximum height. They kept their hands on their hips for the entire course of the jump and were instructed to minimize lateral and horizontal displacements (ie, $x$- and $y$-axes) by jumping vertically (ie, $z$-axis) and landing directly on the force plate.

**ACMJs**

The process of performing the preloaded jumps was similar to that described for the FCMJ; however, an elastic band was attached to either side of a harness worn by subjects at the hip level. The bands were manually stretched and kept beneath the feet of 2 research assistants at either side of the participant. They were released once the subject reached the lowest point of the CMJ, when their hip and knee were fully flexed. Based on this method, subjects would experience additional tensile force of the elastic bands during the eccentric phase of the jump, while they were free to reach a maximal jump.
height without restriction from the bands. The 2 research assistants were well practiced in maintaining the tension of the elastic bands and timing the release of the tension on them. They undertook this procedure throughout the experiment, which reduced the possibility of unsynchronized release of the elastic bands. The resting length of elastic material (Hygienic Corp, Akron, OH) for each subject was 50% of the distance from origin (the harness) to the axis of the elastic band (on the ground, underneath the feet of the 2 research assistants). This was assessed when subjects were standing in an upright position with hips and knees fully extended. Based on this method, recommended by Page and Ellenbecker,\textsuperscript{15} the elastic bands at each side of the participant were stretched 100% and provided adequate downward tensile force. The resistance of the bands was adjusted (tightened or loosened) to provide additional vertical load of 20% (ACMJ-20) and 30% (ACMJ-30) of each participant’s body mass he stood on the force plate with fully extended knee and hip joints. To achieve these particular loads, different combinations of elastic color codes were examined.\textsuperscript{16} It is worth mentioning that each color code of elastic material denotes a specific resistance. The reliability of external force provided by elastic material (Hygienic Corporation, Akron, OH) has been well established and extensively discussed elsewhere (for a review, see Page and Ellenbecker\textsuperscript{15} and Simoneau et al\textsuperscript{17}).

Motion-capture software (Vicon Nexus 1.2) was used to digitize body landmarks. The best trial was selected for each condition based on the highest displacement achieved for each condition. Based on frequency content analysis of the data, marker trajectories were filtered at 10.5 Hz using a fourth-order Butterworth filter. The trajectories of the greater trochanter (250 Hz) and the force plate (1000 Hz) were used to measure displacement and vertical ground-reaction force (VGRF), respectively. Each jump was divided into 3 different phases: the eccentric segment (from initiation of movement until observing minimum GRF), the transition segment (from the minimum GRF until the end of the eccentric phase), and the concentric segment (from the moment after the end of the eccentric phase until the moment GRF is zero). Peak power was calculated based on the method described by Dugan et al,\textsuperscript{18} in which peak power was a product of velocity and GRF observed near the point at which maximal velocity was observed ($v_i = \frac{dx}{dt}$ and $P_i = F_i \times v_i$). Peak VGRF for all subjects was observed at the initiation of the concentric phase. In addition, net impulse was the product of average GRF and time during the propulsive phase of the CMJs (ie, from the point when displacement values reached a maximum depth until the force–time curve returned to zero). Net impulse was calculated by removing the vertical impulse produced from interaction effect of body mass (kg) × gravity (9.8 m/s$^2$). Net impulse values were then divided by the subject’s body mass to determine relative net impulse.\textsuperscript{19,20} Eccentric rate of force development was calculated by dividing the peak eccentric VGRF by the time from initiation of the eccentric phase to the peak eccentric VGRF.

Leg stiffness was calculated based on a spring-mass model at the point when the subject was at the lowest position of the CMJ. At this point, leg stiffness was calculated by the formula $K_{leg} = F_{max}/\Delta h_{hip}$, where $F_{max}$ was maximal VGRF and $\Delta h_{hip}$ was vertical displacement of hip from the start to the point at which the subject was at his lowest position of the CMJ.\textsuperscript{21} Normalized GRF was derived from the measured GRF divided by the subject’s body weight.

Statistical Analyses

Standard statistical methods were used to calculate means and SDs for all variables. Intraclass correlation coefficient was used to determine reliability of jumping tests (Table 1). A series of paired-sample $t$ tests was used to compare variables among the 3 conditions (FCMJ, ACMJ-20, and ACMJ-30) of CMJ exercises. Significance was defined as $P < .05$.

**Results**

The peak power was increased in ACMJ-30 compared with FCMJ (23.21%, $P = .004$) by increasing both the maximal concentric VGRF (6.34%, $P = .031$) and concentric velocity (14.28%, $P = .025$). Neither of these variables achieved a level of significance during performance of the ACMJ-20 compared with the FCMJ. Subjects showed a significantly greater peak concentric impulse (19.07%, $P = .00$) and jump height (9.52%, $P = .035$) by increasing VGRF and contact time (11.42%, $P = .001$) in the ACMJ-30 compared with the FCMJ. The data presented in Table 2 show that time to reach the peak concentric velocity was statistically reduced in both the ACMJ-20 (42.85%, $P = .00$) and the ACMJ-30 (50.00%, $P = .00$) compared with the FCMJ.

The magnitude of leg stiffness, eccentric VGRF, and hip displacement are presented in Table 3. No significant difference was observed in the magnitude of leg stiffness between the 3 modes of jumping, despite there being significantly greater normalized eccentric VGRF for both ACMJ-30 and ACMJ-20 compared with FCMJ when subjects were at the lowest position of the CMJ (all $P < .05$). Vertical displacement of the hip ($\Delta h_{hip}$) increased significantly during the ACMJ-30 compared with the FCMJ (Table 2, $P < .05$).

<table>
<thead>
<tr>
<th>Table 1 Intraclass Correlation Coefficients for Peak VGRF, Peak Power, Velocity, and Jump Height for the 3 Modes of Jump</th>
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<tbody>
<tr>
<td>Free CMJ</td>
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<tr>
<td>Peak VGRF</td>
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<tr>
<td>Peak power</td>
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<tr>
<td>Velocity</td>
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<tr>
<td>Jump height</td>
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Abbreviations: VGRF indicates vertical ground-reaction force; CMJ, countermovement jump; ACMJ-20, accentuated eccentric CMJ with downward tensile force equivalent to 20% body mass.
The purpose of the current study was to investigate the effects of using the additional tensile force of elastic bands in the eccentric phase of a CMJ on kinetic and kinematic characteristics of a vertical jump and the associated leg-stiffness adjustments. The results indicate that using downward tensile force during the lowering phase of a CMJ and releasing the bands at the start of the concentric phase enhances power output, net impulse, and jump height in ACMJ-30 compared with FCMJ. The importance of this finding resides in the fact that these mechanical variables have been declared critical for successful athletic performance.8,20 The findings are in line with the results reported by Sheppard et al.,5 who observed a significant increase in jump height, peak force, peak power, and peak velocity of the accentuated block jump (in volleyball). In the study of Sheppard et al.,5 subjects held 2 dumbbells (10 kg) in each hand and released the dumbbells at the bottom of the squatting phase of a block jump. Sheppard et al attributed the improvement in jumping performance to stretching the series and parallel elastic components and recovery of stored elastic energy during the concentric phase of the jump and further stretching of the intrafusral muscle fiber and provoking of the extrafusral muscle fibers that may increase neural stimulation. However, the rate of muscle activation and the magnitude of leg stiffness were not measured in their study, and they did not elaborate on how additional activation of the motor-unit pool can be achieved by overlaying stretch-reflex excitation over the top of a system that is already under maximal drive.

The results of the current study reveal that using additional elastic force did not change the magnitude of leg stiffness. Given that leg stiffness is the ratio of VGRF and maximum displacement of leg spring, increasing GRF and reducing vertical displacement during the braking phase of the SSC increases leg stiffness and enhances jump height and power output. Although this improvement of performance has been attributed to enhanced muscle activation (motoneuron pool) throughout the rapid stretch of intrafusral muscle fibers and the resultant α-afferent activation,12,22 there is scientific evidence questioning this speculation after observation of similar EMG recordings during the performance of maximal levels of contraction in SSC movements.23 In the current study, despite increasing peak eccentric GRF in the ACMJ-30, no change was observed in magnitude of

<table>
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<th>Condition</th>
<th>Free CMJ</th>
<th>ACMJ-20</th>
<th>ACMJ-30</th>
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</thead>
<tbody>
<tr>
<td>Peak power (W)</td>
<td>66.41 ± 30.31</td>
<td>68.35 ± 31.83</td>
<td>86.49 ± 43.36*</td>
</tr>
<tr>
<td>Mean power (W)</td>
<td>55.16 ± 29.44</td>
<td>56.43 ± 26.31</td>
<td>69.38 ± 37.41*</td>
</tr>
<tr>
<td>Mean concentric force (N)</td>
<td>1523.23 ± 259.32</td>
<td>1561.93 ± 202.80</td>
<td>1585.35 ± 202.24*</td>
</tr>
<tr>
<td>Peak concentric force (N)</td>
<td>1829.57 ± 283.25</td>
<td>1840.62 ± 505.33</td>
<td>1947.06 ± 205.52‡</td>
</tr>
<tr>
<td>Peak eccentric force (N)</td>
<td>1630.07 ± 344.34</td>
<td>1699.01 ± 264.02</td>
<td>1747.88 ± 293.48</td>
</tr>
<tr>
<td>Peak concentric velocity (m/s)</td>
<td>0.36 ± 0.16</td>
<td>0.36 ± 0.17</td>
<td>0.42 ± 0.21*</td>
</tr>
<tr>
<td>Peak eccentric velocity (m/s)</td>
<td>0.18 ± 0.06</td>
<td>0.22 ± 0.11</td>
<td>0.24 ± 0.10*</td>
</tr>
<tr>
<td>Jump height (m)</td>
<td>0.38 ± 0.03</td>
<td>0.40 ± 0.03†</td>
<td>0.42 ± 0.03*</td>
</tr>
<tr>
<td>Time to peak concentric velocity (s)</td>
<td>0.14 ± 0.12‡¶</td>
<td>0.08 ± 0.08</td>
<td>0.07 ± 0.05</td>
</tr>
<tr>
<td>Contact time (s)</td>
<td>0.24 ± 0.03</td>
<td>0.26 ± 0.05</td>
<td>0.28 ± 0.05*</td>
</tr>
<tr>
<td>Time to peak eccentric phase (s)</td>
<td>0.46 ± 0.10</td>
<td>0.40 ± 0.06</td>
<td>0.37 ± 0.03*</td>
</tr>
<tr>
<td>Flight time (s)</td>
<td>0.49 ± 0.03</td>
<td>0.50 ± 0.03</td>
<td>0.52 ± 0.02*</td>
</tr>
<tr>
<td>Relative net impulse (N · s⁻¹ · kg⁻¹)</td>
<td>2.46 ± 0.55</td>
<td>2.76 ± 0.59</td>
<td>3.04 ± 0.53*</td>
</tr>
<tr>
<td>Normalized rate of force development (N · s⁻¹ · kg⁻¹)</td>
<td>48.26 ± 13.90</td>
<td>56.24 ± 14.45</td>
<td>60.57 ± 11.09*</td>
</tr>
</tbody>
</table>

Abbreviations: CMJ indicates countermovement jump; ACMJ-20, accentuated eccentric CMJ with downward tensile force equivalent to 20% body mass.
*Significantly greater than free CMJ. †Significantly greater than free CMJ. ‡Significantly greater than ACMJ-20. ¶Significantly greater than ACMJ-30.

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<th>ACMJ-30</th>
</tr>
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<tbody>
<tr>
<td>Vertical ground-reaction force at end of eccentric phase (N)</td>
<td>1585.45 ± 333.60</td>
<td>1712.28 ± 273.02†</td>
<td>1773.87 ± 377.88*</td>
</tr>
<tr>
<td>Vertical displacement of hip (m)</td>
<td>0.30 ± 0.20</td>
<td>0.33 ± 0.30</td>
<td>0.34 ± 0.30*</td>
</tr>
<tr>
<td>Normalized ground-reaction force (N/kg)</td>
<td>2.08 ± 0.24</td>
<td>2.27 ± 0.29†</td>
<td>2.34 ± 0.35*</td>
</tr>
<tr>
<td>Normalized leg stiffness (N · m⁻¹ · kg⁻¹)</td>
<td>6.88 ± 1.06</td>
<td>6.93 ± 1.31</td>
<td>7.26 ± 1.26</td>
</tr>
</tbody>
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**Discussion**

The purpose of the current study was to investigate the effects of using the additional tensile force of elastic bands in the eccentric phase of a CMJ on kinetic and kinematic characteristics of a vertical jump and the associated leg-stiffness adjustments. The results indicate that using downward tensile force during the lowering phase of a CMJ and releasing the bands at the start of the concentric phase enhances power output, net impulse, and jump height in ACMJ-30 compared with FCMJ. The importance of this finding resides in the fact that these mechanical variables have been declared critical for successful athletic performance.8,20 The findings are in line with the results reported by Sheppard et al.,5 who observed a significant increase in jump height, peak force, peak power, and peak velocity of the accentuated block jump (in volleyball). In the study of Sheppard et al.,5 subjects held 2 dumbbells (10 kg) in each hand and released the dumbbells at the bottom of the squatting phase of a block jump. Sheppard et al attributed the improvement in jumping performance to stretching the series and parallel elastic components and recovery of stored elastic energy during the concentric phase of the jump and further stretching of the intrafusral muscle fiber and provoking of the extrafusral muscle fibers that may increase neural stimulation. However, the rate of muscle activation and the magnitude of leg stiffness were not measured in their study, and they did not elaborate on how additional activation of the motor-unit pool can be achieved by overlaying stretch-reflex excitation over the top of a system that is already under maximal drive.

The results of the current study reveal that using additional elastic force did not change the magnitude of leg stiffness. Given that leg stiffness is the ratio of VGRF and maximum displacement of leg spring, increasing GRF and reducing vertical displacement during the braking phase of the SSC increases leg stiffness and enhances jump height and power output. Although this improvement of performance has been attributed to enhanced muscle activation (motoneuron pool) throughout the rapid stretch of intrafusral muscle fibers and the resultant α-afferent activation,12,22 there is scientific evidence questioning this speculation after observation of similar EMG recordings during the performance of maximal levels of contraction in SSC movements.23 In the current study, despite increasing peak eccentric GRF in the ACMJ-30, no change was observed in magnitude of
leg stiffness, because subjects undertook a significantly greater vertical displacement during the ACMJ-30 than the FCMJ (Figure 1). On this basis, the possible contribution of the stretch reflex and contractile elements seems to be minimal in producing the greater power output observed in the ACMJ-30. Instead, as presented in Figure 2, the attainment of significantly greater force at the onset of the shortening phase and greater extension of serious elastic elements reinforces the contribution of the muscle–tendon interaction effect in producing significantly greater stretch-induced gains in muscle function during performance of the ACMJ-30 compared with the FCMJ. In line with this assumption, it has been demonstrated that greater prestretch of a muscle during the eccentric phase enhances force and power production during a subsequent concentric movement.4

Figure 1 — The force-deformation relationship for the leg during 3 types of countermovement jump (CMJ) demonstrated by the ground-reaction-force (GRF) -displacement curves for the 3 types of CMJ in 1 subject. Despite increasing peak eccentric GRF in ACMJ-30, no change was observed in magnitude of leg stiffness because subjects undertook a significantly greater vertical displacement during ACMJ-30 than FCMJ. FCMJ indicates free CMJ; ACMJ-20, accentuated eccentric CMJ with downward tensile force equivalent to 20% body mass.

Figure 2 — Ground-reaction-force (GRF) curve and GRF–time and displacement–time curves for the 3 types of countermovement jump (CMJ) in 1 subject. Peak eccentric GRF for all 3 jumps happened when the subject was at the lowest position of the CMJ. Subjects experienced a greater magnitude of peak eccentric vertical GRF in a shorter period of time during accentuated CMJs than during FCMJ. ACMJ-20 indicates accentuated eccentric CMJ with downward tensile force equivalent to 20% body mass; FCMJ, free CMJ; $F$, force; $\Delta_{\text{hip}}$, vertical displacement of the hip from the start to the point at which the subject was at the lowest position of the CMJ.
A direct comparison of findings in the current study and those of previous investigations is not possible due to differences in jump technique. However, the relative increase of mechanical variables from free to accentuated CMJ in our study compared with the experiment conducted by Sheppard et al\(^5\) shows that subjects in the current study demonstrated greater improvement in power output (23.22% vs 9.39%), VGRF (6.54% vs 3.89%), and jump height (9.52% vs 4.31%). It is worth mentioning that the downward external load used for all subjects in our study (30% of body mass) was 22.47 ± 1.90 kg compared with the 20-kg dumbbells in the Sheppard et al experiment. A potential explanation for the results could be the difference in the pattern of the provided external load when using dumbbells compared with elastic bands. In fact, the magnitude of load when using free weights is constrained by the effect of gravity (ie, 9.8 m/s\(^2\)), while the recoil force of elastic material provides a loading pattern that depends on the extensibility and stiffness of the elastic bands\(^,\text{15,17}\). Therefore, the recoil force of the elastic device created a greater eccentric velocity increase than the dumbbells (14.28% vs 3.09%). In the current study, the subjects rapidly shortened the unloaded phase and the commencement of the transition phase, developing GRF while continuing to lengthen the quadriceps as the body was lowered. The GRF curves in Figure 2 indicate that subjects experienced a greater magnitude of peak eccentric VGRF in a shorter period of time during accentuated CMJs compared with the FCMJ. Increasing segment velocity during the eccentric phase, due to the contribution of the elastic bands, has been shown to improve peak power\(^,\text{8}\). This phenomenon was attributed to the effect of faster eccentric loading on the preparatory active state of actin-myosin cross-bridge formation before the concentric phase\(^,\text{5}\). Kubo et al\(^24\) also implied that a faster prestretch of human muscle led to greater muscle-tendon-complex lengthening and resulted in considerably greater work performed in the following concentric phase. This speculation has also been supported by studies that have suggested that maximum eccentric velocity is a good predictor of CMJ performance\(^,\text{20,25}\).

In an attempt to maximize power output during CMJ, Argus et al\(^9\) used downward tensile force of elastic resistance throughout both eccentric and concentric phases of CMJ. In their study, despite subjects\(^\prime\) attaining a greater GRF, smaller movement velocity and peak power output were observed during resisted CMJ than during an FCMJ. The reason for this disparity of findings is not clear; however, a potential explanation for observing relatively greater power output during ACMJ in the current study could be that in the Argus et al experiment,\(^9\) subjects performed resisted CMJ against equal magnitudes of elastic force applied during both concentric and eccentric phases. In our investigation, however, release of the elastic bands at the start of the concentric phase enabled subjects to increase concentric velocity and reach maximal jump height without restriction. Previous studies demonstrated that if the concentric phase of a CMJ begins from a higher level of force (ie, imposition to greater GRF during eccentric and transition phases of an ACMJ-30), greater mechanical work could be performed during the first 300 milliseconds of shortening\(^,\text{26}\). In light of this observation, releasing elastic force at the beginning of the concentric phase might facilitate this mechanism and enhance the stretch-induced gains in muscle function. The importance of this finding is related to the proposition that power output and jump height are the key parameters for successful athletic performance, and any training method that improves power production improves sports performance, particularly in jumping aspects of sport\(^,\text{21,25–27}\).

Another important parameter that has a significant predictive value for CMJ performance is the net impulse, which is the product of average VGRF and contact time\(^,\text{21}\). To our knowledge, this is the first investigation that calculated the effect of using the additional elastic force during the eccentric phase of a CMJ on the relative net impulse value. Results of the current study demonstrate a 19.07% greater net impulse for the ACMJ-30 than the FCMJ. This is the product of a 3.91% increase in concentric VGRF and 14.28% increase in contact time. The contact time in the current study was determined from initiation of the eccentric phase to the point of leaving the force plate (Figure 2). This increase in net impulse during accentuated CMJ could indirectly be associated with the leg-stiffness value. Given that contact time is a determining factor in the magnitude of net impulse, increasing the displacement of leg spring during ACMJ-30 extends the contact time, which increases the net impulse value. Accordingly, prevention of an increase in leg stiffness due to greater displacement of leg spring has in return resulted in development of the net impulse.

Overall, although this study validates using ACMJ-30 to achieve higher power production and jump height among trained athletes, our comments are speculative as to whether adaptation to the accentuated eccentric-loading exercises using elastic resistance could result in even further neuromuscular adaptation and improved athletic performance. In addition, there is significant evidence that increasing the segment velocity and force during the eccentric phase requires a greater muscle force to decelerate the load at the end of the eccentric phase\(^,\text{5,10}\). This has been shown to disrupt the contractile proteins and connective tissue of recruited muscle fibers\(^,\text{3,8}\); although it is difficult to pinpoint the actual threshold for the strain. Animal studies have found small focal disruption to muscle fibers of tibialis anterior and extensor digitorum longus when these muscles were passively stretched 30% beyond their resting length\(^,\text{29}\). In practice, however, it is most unlikely that a muscle is able to withstand being stretched to this extent without incurring damage to the contractile units. Further investigation is needed to determine whether the eccentric force and velocity of an accentuated CMJ might exacerbate the propensity for ultrastructural muscle damage.

### Practical Application

The findings of the current study imply that using downward recoil force of elastic bands during the eccentric phase of a CMJ is an effective method of increasing
jump height and peak power output. The ACMJ-30 could particularly be a useful plyometric exercise for athletes who are at their peak muscle strength and power-output capability and need a novel mode of exercise to overcome their current plateau stage of performance. Thus, accentuated CMJ using elastic bands could be used to develop lower extremity power output and jump height during preparatory and competitive phases of training protocols.

References