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Differences between vertical jumps in elite female volleyball players. Reasons for lack of differences

MARKO JOKSIMOVIC[1], STEFANIA D’ANGELO[2], NEBAHAT ELER[3], SINIŠA KARIŠIK[4], NEMANJA ZLOJUTRO[5], FRANCESCA LATINO[6], DOMENICO TAFURI[2]

Abstract

Introduction. Squat jumps (SJ) and countermovement jumps (CMJ) are commonly used as tests to assess power output of lower extremities. Aim of Study. The aim of this article was to analyze differences between two vertical jumps in order to assess explosive power in elite female volleyball players and identify mechanisms responsible for existence of those differences. Material and Methods. Participants of this study were 14 elite female volleyball players of the Montenegro U19 national team (age: 18.42 ± 1.34 years; height: 178.15 ± 4.9 cm; weight: 68.1 ± 5.83 kg; body mass index: 21.34 ± 1.10 kg/m^2; body fat: 18.89 ± 3.70%). Jump height data for a SJ and a CMJ was obtained using OptoJump device (Optojump, Microgate, Bolzano, Italy). Results. The results showed that there is no statistically significant difference ($F = 0.093$, $p < 0.124$) between the heights of the SJ (26.64 ± 2.93 cm) and the CMJ (26.65 ± 2.85 cm). Conclusions. The findings suggest that elastic energy has very little effect on improving CMJ performance. On the other hand, CMJ training can reduce an ability to effectively create pre-tension and quickly build stimulation, because athletes are not forced to do so, as the CMJ reduces a degree of muscle relaxation and provides more time to create stimulation. Based on the data, the CMJ may be detrimental to high-intensity sports performance if performed over a longer time frame.

KEYWORDS: jump height, volleyball, squat jump, countermovement jump, differences.

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Corresponding author: nicifor007@outlook.com; marko.j@ucg.ac.me

[1] *University of Montenegro, Faculty of Sport and Physical Education, Podgorica, Montenegro*

[2] *Parthenope University of Naples, Department of Movement Sciences and Wellness, Naples, Italy*
[3] *Gazi University, Faculty of Sport Science, Ankara, Turkey*
[4] *University of East Sarajevo, Faculty of Physical Education and Sport, Sarajevo, Bosnia and Herzegovina*
[5] *University of Banja Luka, Faculty of Sport and Physical Education, Banja Luka, Bosnia and Herzegovina*
[6] *Pegaso Telematic University, Faculty of Human Science, Naples, Italy*

Introduction

Squat jumps (SJ) and countermovement jumps (CMJ) are commonly used as tests to assess power output of lower extremities. Comparing results obtained in such tests allows better understanding of a stretch-shortening cycle (SSC) contribution, which includes elastic energy storage during an eccentric phase and subsequent energy release during a next concentric contraction. Preactivation is important during the eccentric phase and for timing of muscle activation in relation to ground contact, where the muscle activation regulates muscle stiffness; a stretch reflex of an active, stiff muscle during the eccentric phase of a lift stores elastic energy in transverse bridges and tendons. It has been shown that the elastic energy can be used during the concentric phase of muscle contraction [55]. Muscle architecture has been found to be related to SSC performance in vertical jumps [1, 12, 33]. Regarding a vertical jump, Earp et al. [12] stated that a higher gastrocnemius pination angle is a significant predictor of SJ and CMJ performance. It has been suggested that a difference between the CMJ and the SJ is caused by a performance enhancement effect of the SSC during the CMJ [39]. Results of these performance differences can be used to measure the contribution of the SSC, with a greater difference between the CMJ and the SJ indicating better use of the SSC. Komi and Bosco [27], point that greater height achieved in the CMJ is a result of better storage and utilization of the elastic energy during the CMJ. Bosco et al. [9] indicate that a difference between the SJ and the CMJ can serve as an indicator of fiber type distribution, after finding a correlation among a fiber type, a vastus lateralis muscle and a difference in mean force between the CMJ and the SJ. Other studies report that the difference between the CMJ and the SJ provides an estimate of pre-stretch increases [56] or reactive power under slow cycle conditions [57]. In both studies, the greater difference between the jumps indicates a superior ability to use the SSC. On the other hand, McGuigan et al. [39] state that performance differences between the CMJ and the SJ are probably not primarily due to elastic energy storage and utilization, but the authors suggest that an Eccentric Utilization Ratio (EUR) would be a more appropriate term as it reflects an effective use of the eccentric phase during the CMJ. The authors state that the greater difference between the jumps, as indicated by the higher EUR, would indicate a better ability to use the eccentric phase. These studies indicate that the difference in height achieved or power produced during the CMJ and the SJ is due to an efficient use of the SSC, while the greater difference between the jumps is an indication of a better ability to use the SSC. However, these studies did not answer which mechanisms are responsible for the performance enhancement effect of the SSC, which is why it is necessary to understand these mechanisms in order to draw a conclusion about the difference between the jumps. For example: if storage and utilization of the elastic energy were primarily responsible for greater acute performance during the CMJ, the larger difference between the SJ and the CMJ would be beneficial as this reflects the greater ability to store and use the elastic energy. However, if acquisition of muscle relaxation is responsible for better acute performance during the CMJ, the greater difference between the SJ and the CMJ is not desirable because it reflects muscle relaxation due to a poor ability to develop pre-tension through muscle coactivation [49]. Accordingly, the aim of this article was to analyze differences between two vertical jumps in order to assess explosive power in elite female volleyball players and identify mechanisms responsible for existence of those differences.

Methods

Participants

This was a cross-sectional study. Participants completed testing procedures as a part of their routine assessments, so no separate familiarization session was conducted. For this study, 14 elite female volleyball players of the Montenegro U19 national team (age: 18.42 ± 1.34 years; height: 178.15 ± 4.9 cm; weight: 68.1 ± 5.83 kg; body mass index: 21.34 ± 1.10 kg/m^2; body fat: 18.89 ± 3.70 %) were recruited. The study was conducted during preparations for European Championship qualifications. The players were asked not to perform any resistance exercises or very exhaustive training in general for two days before measurements and testing. They were also asked to maintain their normal eating habits and to refrain from drinking alcohol for two days before the measurements and testing. All players compete in the first national league, the highest competitive level in Montenegro. The players stated that they had been involved in regular training for five years, attending 5.7 ± 1.2 training sessions per week and regularly performing full-body resistance exercises at least twice a week. Inclusion criteria were as follows: being in a first league team for at least six months, having gone through a preparatory period with a team, lack of injuries in the last six months, having played one half-season before the testing. Exclusion criteria were: female players in recovery from any form of acute or chronic injury and female players who did not complete an entire preparatory period. All participants were informed about experimental procedures and had to sign an informed consent form before participating in the experiment. Parents or legal guardians signed the consent forms on behalf of underage participants. The experiment was approved by the National Volleyball Association and the coach of the U19 national team, and was conducted in accordance with the Declaration of Helsinki. The players have been in the first team for at least six months, all the female players have gone through the preparatory period with the team, they have had no injuries in the last six months, and have played one half-season before the testing.

Testing procedures

The participants performed a warm-up consisting of 10-minute easy running on a closed track, 5-minute dynamic stretching, 5-minute body mass resistance exercises (squats, lunges, push-ups) and 3-minute activation exercises (vertical jumps). The two types of the vertical jumps were tested: the SJ and the CMJ. The CMJs were tested with an Optojump device [20] by placing the players in a limited area covered by Optojump's sensors. The participants started the test in an upright position with their hands on their hips, and upon a sound signal, they jumped as high as possible from a semi-squat position reflected. Three technically correct jumps were required and the best result was used for analysis. The SJs also were tested with the Optojump device. The test was performed by the subjects in a following way: the participants started in the semi-squat position with their hands on their hips, holding it for 2 seconds. Upon the sound signal, the subjects bounced from the initial position into a vertical jump. Each test was repeated three times, and the best results were used for analysis [20].

Statistical analysis

All data collected through the research were processed using descriptive and comparative statistics. Regarding the descriptive statistics, a mean and a standard deviation were measured for each variable. Normality of distribution of the variables was derived through two procedures: asymmetries of skewness results and homogeneity of kurtosis results. Regarding the comparative statistics, a discriminant parametric procedure was used: analysis of variance with one-way ANOVA and post hoc analysis, which determined differences between the vertical jumps. The statistical procedures were executed on the SPSS software (version 26.0, IBM, United States) for p set at 0.05.

Results

Table 1 presents basic descriptive parameters for the SJ and the CMJ. The analysis of the results in Table 1 shows that there are no deviations from the normal distribution. Table 2 presents the differences for two vertical jumps, the SJ and the CMJ. The analysis of Table 2 shows that there are no statistically significant differences between the vertical jumps.

Table 1. Descriptive statistics for the squat jump and the countermovement jump

Jumps	Mean ± SD	Range		Skewness	Kurtosis
		Min.	Max.		
Squat jump	26.64 ± 2.93	21.4	30.9	–0.536	–0.461
Countermovement jump	26.65 ± 2.85	20.7	31.3	–0.555	0.130

Note: SD – standard deviation, Min. – minimum, Max. – maximum

Table 2. Differences between the vertical jumps

Jumps	Mean ± SD	ANOVA	
		F	Sig.
Squat jump	26.64 ± 2.93	0.093	0.124
Countermovement jump	26.65 ± 2.85		

Note: SD – standard deviation, F – ratio of two variances, Sig. – significance

Discussion

The aim of this article was to analyze the differences between two vertical jumps in order to assess explosive power in elite female volleyball players and identify the mechanisms responsible for the existence of those differences. To better understand the mechanism that explains the improvement in the CMJ performance, it is necessary to consider an interaction of muscles and tendons. The SSC is ambiguously described as muscle stretching followed by a shortening phase. However, muscles' parts that are stretched and shortened are not distinguished, which leads to misinterpretation. For example, it is assumed that there is an eccentric action of fascia of leg muscles during a downward movement of the CMJ. Some studies have shown that lengthening of fascia during the downward phase of the CMJ is largely passive and occurs primarily, but not exclusively, in monoarticular muscles [15, 16, 17]. Studies show shortening of fascia [16, 34], or suggest an isometric action of an contractile element during a descending phase of the CMJ [28, 29], which is why there is usually no active lengthening of fascia during the downward movement of the CMJ. Fasciae can passively lengthen during slow, submaximal, and high-amplitude CMJs, thereby dissipating energy, while remaining isometrically or concentrically contracted during fast, maximal, or low-amplitude jumps [28, 29, 47]. These studies recommend that future studies refer to the downward and upward phases rather than the concentric and eccentric phases of the CMJ, and avoid terminology related to the eccentric phase. Attributing the difference between the CMJ and the SJ to the effective use of the eccentric phase and the mechanism that occurs during the eccentric muscle actions is problematic because there may be no eccentric phase during the CMJ. Better acute performance in the CMJ may be a result of other mechanisms [50].

When an activated muscle is lengthened, steady-state isometric force production after lengthening is greater than the corresponding force in an isometric action in a similar manner. This effect is called residual force enhancement [24] or potentiation [14]. An increase in residual force occurs during the CMJ and may partially explain the superior acute performance during the CMJ. A contribution of the increasing residual force by increasing force during the CMJ is likely to be minimal because muscle fibers can only lengthen during slow, high-amplitude CMJs [28, 29, 47], while remaining isometric [28, 29], or contract concentrically [34] during fast and low-amplitude CMJs. When the muscle fibers lengthen during the downward phase, it is usually passive lengthening [15, 16, 17]. Based on this, there may be no active lengthening and no increase in the residual force during the CMJ. The increase in residual force increases with magnitude of the muscle fibers lengthening, is largely independent of lengthening velocity, and decreases with time elapsed after lengthening, with much of the increased force decaying within approximately one second [18, 24]. If there is active lengthening of muscle fibers during a slow, high-amplitude CMJ, this will lead to a relatively slow stretch and a significant amount of time will elapse between stretch and recovery contraction [4], reducing the residual force enhancement effect. In support of this, based on in vivo human experiments [16, 52], several authors have concluded that effects of increasing residual force in in vivo movements are essentially small. The reason is that a delay between a possible active extension and maximal force production is relatively long [4]. Laxity in fascia, tendon tissues, and an overall muscle-tendon unit, increased pination angle, and tendon tissue compliance can reduce the stretch applied to the muscle fibers [49] and thus reduce the effects of increasing residual force. If there is active lengthening of muscle fibers and an increase in residual force, a contribution to improve acute performance during a CMJ is probably small [50].

The mechanism believed to be responsible for the greater acute effect observed during the CMJ is increased muscle activation due to an activated stretch reflex. When muscle fibers are stretched or when vibration waves travel through a muscle, a muscle spindle can trigger both short- and long-latency reflexes that engage additional motor units or increase firing rate of the engaged motor units [10, 11, 42]. These mechanisms increase force production during the descending and ascending phases of the countermovement, thereby improving CMJ performance. Muscle spindles are sensitive not only to stretch amplitude, but also to stretch velocity [36], resulting in a greater stretch reflex due to higher velocities [35]. It was observed that the reflex is triggered only when threshold velocity is reached and is variable, depending on training, muscles, and individual differences within muscles, such as motor units composition or muscle spindle density [45]. During the downward movement of the CMJ, average angular velocities of an ankle, a knee, and a hip are approximately 0°, 133-199°, and 216° per second, respectively [16, 34]. For the knee and hip joints, these average angular velocities are greater than the angular velocities at which the stretch reflex is elicited during passive ankle dorsiflexion (i.e., 69° per second) [44]. The angular velocity of the ankle joint is lower than the angular velocity at which the stretch reflex is elicited in plantar flexors during passive ankle dorsiflexion [44]. Based on the angular velocities of the joints, it remains unclear whether the stretch reflex is elicited in the muscles spanning the hip and knee joint during the downward phase of the CMJ. According to Van Hooren and Zolotarjova [50], it seems unlikely that the stretch reflex is elicited for the plantar flexors based on the average ankle angular velocity. As noted earlier in the present study, the muscle fibers do not necessarily lengthen during the downward countermovement phase [29, 34]. Although the angular velocities of the joints are large enough to elicit the stretch reflex, the reflex may not be elicited if there is no lengthening of the muscle fibers. By relaxing intrafusal muscle fibers, the muscle spindle can be tuned to activate only when a certain muscle length is reached. When this muscle length is adjusted to match a length greater than the length achieved during the countermovement, the reflex may not be triggered at all. Therefore, the angular velocities of the joints, the lengthening of the muscle fibers, and the stretching of the muscle spindle do not necessarily correspond.

These findings explain why some studies reported greater surface electromyographic activity of the plantar flexors during the concentric phase of the CMJ [32], while other studies reported similar electromyographic activity of the plantar flexors in the SJ and the CMJ [21] or found no significant difference in electromyographic activity of calf and upper leg muscles between the SJ and the CMJ [4]. These studies suggest that the stretch reflex will not be elicited in the low-amplitude CMJs when no muscle fiber lengthening is present, whereas it can be elicited in the high-amplitude submaximal CMJs if the muscle fibers are lengthened and the threshold velocity is reached. It is noteworthy that the short-latency stretch reflex was found to be weakly associated with changes in fascial length and velocity, suggesting that muscle vibration may also play an important role in eliciting the stretch reflex [10]. Ballistic movements, such as vertical jumps, have been found to require maximal activation of motor units, regardless of a rate of muscle shortening during the concentric phase [32, 38]. Since it has been shown that the contribution of the stretch reflex in the lower extremities decreases with the increasing force production and the muscle activation [40, 43, 48], a question can be raised whether the stretch reflex can activate additional motor units or increase the rate of motor unit engagement during the CMJ. In support of this, Bobbert and Casius [3] did not include a stretch reflex in their computational model and found that a height of a CMJ was greater than a height of an SJ, meaning that the stretch reflex had a negligible or no contribution to better acute performance during the CMJ.

If a starting position of a jump is not controlled, most athletes tend to lower the center of mass of a body more in the SJ than in the CMJ [19, 26, 37], a range of motion in which force can be produced is smaller and this may explain lower performance in the SJ. On the other hand, when starting positions are identical or when an athlete starts the SJ from a deeper position than in the CMJ, a jump height is still greater during the CMJ [19, 26, 41], which means that the range of motion with which force is produced does not explain the difference between the jumps.

The mechanism thought to be responsible for the enhanced acute effects during the CMJ is the storage and utilization of the elastic energy. Previous studies have suggested that the elastic energy can be stored in tendons during the downward phase and used during the upward phase to increase force production [8, 27]. On the other hand, some studies claim that the storage and use of the elastic energy does not explain the difference in the jump height between the CMJ and the SJ [2, 3, 34, 51, 52, 53], even though the elastic energy increases force production in the SJ and CMJ performance [16, 47, 59]. During the initial upward phase of the SJ and the CMJ, concentric contractions of the muscle fibers stretch the tendon tissues, which later in the upward phase pull in a catapult-like fashion to increase the force production. This indicates that the storage and utilization of the elastic energy plays a role in both the SJ and the CMJ. As stated earlier, the results of computational modeling and experimental studies suggest that the difference between the jumps can be explained by the fact that only a small amount of additional energy is stored in the tendons during the countermovement at the CMJ [2, 34], while a significant amount of energy is lost as heat during the performance of the CMJ compared to the SJ [28]. Regardless of these statements, it is important to distinguish between the slow, submaximal and high-amplitude CMJs and the fast, maximal and low-amplitude CMJs. In the first CMJ, the elastic energy is unlikely to improve performance because chemical and kinetic energy is dissipated into heat, whereas the elastic energy can be used to improve the CMJ performance in the last CMJ [28, 29, 47]. Research conducted by Kopper et al. [28, 29] points that the contractile element remains isometric during the low-amplitude CMJ, which enables the storage and reuse of the elastic energy in a serial elastic element, while the contractile element passively lengthens during the high-amplitude CMJ, which does not store the minimal elastic energy and dissipate chemical and kinetic energy into heat. Based on this, whether the elastic energy improves the CMJ performance compared to the SJ performance may depend on the amplitude of the countermovement and the effort used during the movement. Whether the elastic energy improves the CMJ performance during the fast, maximal, low-amplitude CMJ may depend on the ability to rapidly increase muscle stimulation and decrease muscle relaxation, with the elastic energy used only when athletes can rapidly increase the muscle stimulation and decrease the muscle relaxation. These results suggest that the elastic energy storage and usage has little effect on increasing acute performance during the slow, submaximal, high-amplitude CMJs, whereas it may have a greater, although probably still relatively small, effect during the fast, maximal, low-amplitude CMJs. The performance improvement of the fast and high-amplitude CMJs compared to the SJs requires further research [50].

None of the mechanisms mentioned so far contribute significantly to the better acute effect of the CMJ compared to the SJ. Mechanisms that may explain the lack of differences between the CMJ and the SJ are stimulation, excitation, and contraction dynamics. Stimulation refers to an increase in muscle stimulation (a rate of increase in electromyographic activity). Excitation refers to development of an active state (a fraction of actin binding sites available for cross-bridge formation) in response to stimulation. Contraction dynamics refers to force development in response to an active state [3, 4, 6]. Muscle stimulation may not reach a maximal level but takes time to develop maximal stimulation due to dynamics of motor neuron excitation and central commands [7]. When a muscle is stimulated, it does not contract immediately due to electrochemical delays associated with action potential propagation across a muscle membrane and excitation-contraction couplings [49, 54, 58], i.e., in relaxed muscles, fascia, tendon tissues, and an overall muscle-tendon unit can be relaxed [22, 23, 49], indicating no passive elastic force production [25]. This laxity must be compensated for, as the tendon tissues must be stretched before force can be transmitted to bones in order to initiate joint movement. The processes associated with taking up slack and stretching tendon tissues are collectively called muscle relaxation [50].

Duration of electrochemical processes is relatively short (approximately 3-6 ms) and it is unlikely that they contribute significantly to a difference between spikes. In contrast to electrostimulation processes, muscle relaxation can last more than 100 ms [49], which is why performance can be significantly improved by reducing muscle relaxation during the countermovement. The countermovement moves attachment points of a musculotendinous unit further, reducing laxity in fascia and tendon tissues, aligning the muscles and tendons, stretching the tendon tissues and enabling faster force transmission [16, 49]. However, when an athlete descends to the initial SJ position, the attachment points of the musculotendinous unit are moved further, reducing a muscle relaxation effect [49]. In the initial position of the SJ, forces should be large enough to counteract only the forces of gravity. In contrast, when the upward motion of the CMJ is initiated, the forces are large enough to counteract the forces of gravity and the downward acceleration of the center of mass. As a result, the ground reaction force and the forces acting on the musculotendinous units are greater during the upward movement in the CMJ compared to the forces acting on the musculotendinous units in the initial SJ position, and therefore the tendon tissues are stretched more during the countermovement due to greater forces [13, 31], resulting in greater tendon tissue stiffness. Greater stiffness may allow muscle fibers to shorten at a slower rate, thereby increasing their ability to generate force and improve the CMJ performance [16].

Research has shown that athletes with stiff tendon tissue show smaller difference between the CMJ and the SJ compared to athletes with mobile tendons [30, 31]. Previously, these findings have been interpreted as evidence that athletes with the mobile tendon tissue can store and use more elastic energy during countermovements and therefore show a greater difference between the SJ and the CMJ. These statements may indicate that those athletes with the mobile tendon tissue benefit more from an effect of countermovement stiffness, while this effect is less pronounced in athletes with the greater tendon tissue stiffness. Although it has been previously suggested that a muscle fiber type may explain the differences between the CMJ and the SJ [9, 51], Kubo et al. [31] reported that it is the tendon tissue stiffness and not the muscle fiber type that influences the difference between the CMJ and the SJ. In their study, the researchers divided athletes into two groups: athletes with high tendon stiffness and athletes with consistent stiffness. The results of the study revealed that the tendon tissue stiffness significantly influenced the difference in performance between the CMJ and the SJ, even though both groups included sprinters, who are expected to have a higher percentage of fast-twitch muscle fibers.

The tendon stiffness may partially explain the difference between the CMJ and the SJ. Using the computational modeling, Bobbert and van Zandwijk [7] found that the countermovement allowed the muscles to build up to high stimulation before jumping. In a later study, the researchers showed that the difference between the CMJ and the SJ decreases with faster muscle stimulation, because a muscle shortening distance traveled in the submaximal active state during the SJ decreases [3]. These findings suggest that the difference between the CMJ and the SJ is partially related to an accumulation of large muscle stimulation during the countermovement, which allows a greater distance to be covered in a maximally active state during the upward phase in the CMJ compared to the SJ [2, 51, 53]. Also, the increase in stimulation and the decrease in muscle relaxation are interrelated, because a faster increase in stimulation would lead to a faster decrease in muscle relaxation, i.e., a rate at which stimulation increases explains a large part (approximately 50%) of dynamic force in athletes during the SJ [6]. Some athletes develop this stimulation slower than others because it can reduce jump height sensitivity to errors in timing of muscle activation [6, 7]. Research has shown that the timing of muscle activation is of great importance for vertical jump performance [5, 7, 46]. Using the computational modeling, it has been shown that a difference of less than 10 milliseconds in plantar flexor activation time during the SJ results in a reduction in jump height of more than 10 cm [7]. These findings suggest that athletes with poor coordination (i.e., poor ability to accurately time muscle activation) perform poorly in the SJ, while still being able to perform relatively well in the CMJ because they can increase stimulation during countermovements. Coordination training can be important for improving performance in high-intensity sport situations, in which it is important to quickly increase stimulation and in which there are almost no countermovements – a block jump in volleyball. These statements indicate that the difference between the height of the CMJ and the SJ is primarily related to the acquisition of muscle relaxation, the accumulation of stimulation, and the corresponding active state during the countermovement in the CMJ [50].

Conclusions

The CMJ is included in the training with the aim of optimizing the SSC, i.e., to improve the storage and use of the elastic energy. The findings presented in this article suggest that the elastic energy has very little effect on improving the CMJ performance. On the other hand, the CMJ training can reduce the ability to effectively create pre-tension and quickly create stimulation, because athletes are not forced to do so, as the CMJ reduces the degree of muscle relaxation and provides more time to create stimulation. Based on the data, the CMJ may be detrimental to high-intensity sports performance, especially when performed without time pressure. Based on all of the above, training should minimize the difference between the CMJ and the SJ performance, with targeted training of these two types of jumps.

Conflict of Interest

The authors report no conflict of interest.

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