

Neuromechanical strategies employed to increase jump height during the initiation of the squat jump

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Abstract

The maximal height attained in a vertical jump is heavily influenced by the execution of a large countermovement prior to the upward motion. When a jump must be executed without a countermovement, as in a squat jump, the maximal jump height is reduced. During such conditions, the human body may use other strategies in order to increase performance. The purpose of this research was to investigate the effects of two strategies employed during the initiation of the squat jump: the premovement silent period (PSP), and the small amplitude countermovement (SACM). Fifteen elite male volleyball players (20.6 ± 1.6 years) and 13 untrained males (20.2 ± 1.7 years) performed 10 maximal effort squat jumps from identical starting positions. The electromyographic activity of the vastus lateralis and biceps femoris was measured in conjunction with the vertical ground reaction force and vertical displacement. It was found that the presence of a PSP or a SACM of 1–3 cm did not increase maximal squat jump height significantly ($p > 0.05$), in neither the highly trained athletes nor the untrained individuals. These results suggest that these strategies do not play a major role in the determination of jump height. Researchers have assumed that a squat jump is purely concentric, and that there are no facilitating mechanisms present that may influence the performance of the jump. This study provides evidence to support this assumption.

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1. Introduction

Vertical jumping is one of the most frequently performed movements in sports, and has been studied extensively in the literature [2,6,7,12,17,19,22]. In most situations, jumping is preceded by a countermovement (rapid flexion of the hip, knee, and ankle joints) prior to push off [6]. When a jump is made from a stationary, semi-squatting position without a countermovement, it is referred to as a squat jump (SJ) [2].

In research, the SJ is routinely used as a comparison to the countermovement jump (CMJ). This is done

primarily to examine the influences of the countermovement in producing higher jump heights, as well as the ability of the neuromuscular system to rapidly develop force [1,6]. The literature is lacking, however, in research directly investigating the strategies used at the beginning of the SJ. If there are specific mechanisms that the body employs, it may assist in explaining why the differences between SJ and CMJ heights reported in the literature are often smaller than expected [2]. There are two strategies, not previously investigated, that may account for this variation in SJ height: the premovement silent period (PSP), and the small amplitude countermovement (SACM).

When a rapid movement must be initiated from a static posture, a PSP has been found to occur prior to the initial muscular contraction [4,14,15]. The PSP can be seen in the electrical activity of the agonist muscle(s), as

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either a complete cessation, or significant reduction in the level of activity. It was first suggested by Conrad et al. [11], that the PSP may assist rapid movements by allowing the motor units that are being excited during static posture to enter into a non-refractory state. This in turn, allows a greater synchronization between the motor units when the concentric muscular contraction begins. In the literature, it has been demonstrated that rapid movements with a PSP present have a significantly higher velocity [11] and rate of force development [3,14,20], than identical movements without a PSP present. It is, therefore, possible for the height of a squat jump to be increased with the occurrence of this phenomenon, considering that the maximum velocity and rate of force development are major determinants of the height of a vertical jump [18].

The PSP has also been demonstrated to be a learned motor response; subjects who trained to produce the PSP using biofeedback were successful in increasing their utilization of the mechanism [21]. In addition, the subjects who were able to learn to produce the PSP most successfully also had the greatest gains in movement velocity [21]. This suggests that individuals who are trained in rapid movements would exhibit the PSP more often, and show greater facilitation, than untrained individuals.

The SJ has been used extensively in research [2,6,7,12,17,19,22]. The SJ, however, is an unnatural movement, in that almost all forceful movements are executed with some degree of preliminary counter-movement. For most individuals, a substantial amount of learning must take place before the movement can be performed correctly. This is evident in the literature, as it is often seen that individuals produce a SACM despite extensive practice and encouragement [7,12,22].

Since many intended SJs are performed with an unconscious SACM, it is important to determine if this has a significant effect on jump height. A SACM may have facilitatory effects by utilizing a small and rapid stretch–shortening cycle. Bosco et al. [8] demonstrated that countermovements of about 55° knee flexion were more efficient, had a greater total positive work, and a greater stretching speed than larger amplitude countermovements of about 87° knee flexion. In a similar study, it was found that individuals with a high percentage of fast twitch muscle fibers benefited most from a stretching phase performed with high speed and small angular displacement [9]. Thus, it can be argued that a highly trained jumper could benefit significantly (increase maximum SJ height) from a SACM, although this has not been empirically tested to the authors' knowledge.

The present study was designed to investigate two possible strategies used by the human body to increase the height of the SJ, in lieu of a large counter-movement. In particular, the influences of a PSP and

SACM on maximal SJ height were examined in both highly trained and untrained jumpers.

2. Methods

2.1. Participants

Fifteen elite male volleyball players and 13 untrained males volunteered to participate in the study. Participant characteristics are presented in Table 1. The volleyball players were from a nationally ranked National Collegiate Athletic Association (NCAA) Division I University team. The untrained participants were all recreationally active, but not specifically trained in any type of vertical jumping. Prior to participating in the study, individuals read and signed a written consent document. The study was approved by a University Ethics Committee.

2.2. Experimental design

Participants attended a single testing session, during which they performed 10 maximal-effort SJs. Electromyographic, kinetic, and kinematic data were synchronized and collected at a frequency of 1 kHz.

2.3. Data recording

Using electromyography (EMG), the electrical activity of the vastus lateralis and biceps femoris muscles was recorded from the right leg using pre-amplified bipolar active surface electrodes (TSD150, Biopac Systems Incorporated, Goleta, CA, USA) with stainless steel discs, and a fixed inter-electrode distance of 2 cm, center to center. The pre-amplified electrodes had a gain of 330, common mode rejection ratio of 95 dB, input impedance of 100 M Ω , and a bandwidth of 12–500 Hz. Prior to application, the electrical impedance of the skin at each site of electrode placement was minimized using standard skin preparation procedures [5]. Electrodes were located on the muscle belly, aligned parallel to the muscle fibers, according to the methods outlined by Basmajian and Blumenstein [5]. A reference electrode was placed on the lateral malleolus of the right ankle. EMG activity for each muscle was passed through a data acquisition unit (MP100A, Biopac Systems Incorporated), which digitized the signal. The signal was then sampled by a software program

Table 1
Mean \pm SD age, height, and mass for all participants

Group	Age (years)	Height (m)	Mass (kg)
Trained ($n=15$)	20.6 \pm 1.6	1.92 \pm 0.05	87.6 \pm 8.9
Untrained ($n=13$)	20.2 \pm 1.7	1.86 \pm 0.03	82.9 \pm 9.6

(Acknowledge version 3.5.2, Biopac Systems Incorporated), and stored on a personal computer for analysis.

The vertical ground reaction force (VGRF) was measured using a force platform (9281B, Kistler Instrument Corporation, Amherst, NY, USA). The raw VGRF data were first amplified (9865A, Kistler Instrument Corporation), and then digitized using an analog-to-digital card (CIO-AD16Jr, ComputerBoards Incorporated, Mansfield, MA, USA). The digitized VGRF data were then sampled by a personal computer using the Ballistic Measurement System data acquisition software (version 1.3.1, Innervations, Muncie, IN, USA), and stored on the hard drive for analysis.

In conjunction with the force platform, a cable-extension transducer (PT9510, Celesco Transducer Products Incorporated, Chatsworth, CA, USA) was used to measure vertical displacement. Displacement data were sampled using the same computer and software as the force platform. The cable of the transducer was attached to the lower back of participants by a belt cinched tightly around their waist.

To validate this method of measuring vertical jump height, a participant was filmed with reflective markers using a digital camera (GR-DVL9800, JVC Company of America, Wayne, NJ, USA) operating at a framing rate of 60 Hz. The displacement of the center of mass was calculated using body segment parameters and regression equations developed by Chandler et al. [10]. A Pearson product moment correlation was performed using data from 10 SJs to determine the relationship between the center of mass displacement (32.6 ± 1.2 cm), and the displacement recorded from the cable-extension transducer (33.9 ± 1.6 cm). This resulted in an *r*-value of 0.85. The percent difference between the two methods was 0.04%.

2.4. Protocol

Participants were instructed to start from a semi-squatted position and to jump for maximal height. The importance of avoiding any kind of preparatory countermovement was stressed. To standardize the starting position, a digital video camera (5100HS, Matsushita Electric Corporation of America, Secaucus, NJ, USA) was placed perpendicular to the participant. This allowed individuals to view themselves on a large television monitor and align their body with a template of their torso and legs, similar to the methods used by Anderson and Pandy [2]. The knee angle for all participants was set at 100° , with 180° defined as a straight leg. Participants were instructed to keep their arms crossed against their chest throughout the jump.

Prior to the data collection, participants warmed up by pedaling a stationary bicycle for 5 min, at a self-selected speed and resistance. Each individual performed five practice SJs. Participants then moved into

position over the force platform, and assumed a self-selected foot position. While the participants stood straight and motionless, the cable-extension transducer was reset to zero. On a verbal cue from the investigator, individuals lowered their body to their pre-set squatting position. Once they were stabilized in this position, data collection was started to allow a baseline of muscle activity to be measured. After 2 s, the command “go” was given and individuals initiated the SJ. Ten maximal effort SJs were performed while data were collected. Participants were given a 1-min rest period between trials.

2.5. Data analysis

It is important to note, that by strict definition, jumps with even a small countermovement present would be considered CMJs. However, in order to avoid confusion, all jumps performed in this study were classified as SJs. Jumps were then further classified as SJs with or without: (1) a PSP present, (2) a SACM present, or (3) a PSP and SACM present simultaneously.

All post processing was performed using custom software developed within the Visual Basic (version 6.0, Microsoft Corporation, Redmond, WA) programming environment. To determine the occurrence of a PSP, raw EMG was first rectified, and the root mean square EMG (rmsEMG) value calculated using a moving average window of 31 ms. If in the 500 ms prior to the initial agonist burst, the level of rmsEMG fell below 2 standard deviations of the mean background level of rmsEMG, it was classified as a SJ with a PSP present. The background level of rmsEMG was defined as the time during which the participant was in the squatting position, beginning at the start of data collection and ending 1.5 s later. In order to avoid transient decreases in rmsEMG being classified as a PSP, the minimum duration accepted for a PSP was 10 ms, based on the work of Mortimer et al. [15].

VGRF data from the force platform were digitally filtered using a bi-directional, low-pass, fourth-order, Butterworth filter, with a cut-off frequency of 7 Hz. Displacement data from the cable-extension transducer were filtered similarly with a cut-off frequency of 7 Hz. Optimal cut-off frequencies were determined using the methods described by Jackson [13]. The presence of a countermovement was determined using the custom software to examine the VGRF trace. The cut-off value was set at 5% of an individual's body weight. If the VGRF dropped below this value during the 500 ms prior to the maximum push-off force, the jump was classified as a SJ with a SACM present.

Table 2
Mean \pm SD jump heights for trained and untrained participants. Heights are based upon whether or not a PSP or a SACM occurred

Condition	Jump height (cm)	
	Trained ^a	Untrained ^b
PSP	46.6 \pm 6.2	46.3 \pm 4.7
No PSP	47.2 \pm 5.0	45.9 \pm 4.0
SACM	50.9 \pm 6.3	45.5 \pm 5.2
No SACM	49.8 \pm 5.0	43.5 \pm 6.4
Both PSP and SACM	48.2 \pm 3.1	48.3 \pm 4.8
Neither PSP nor SACM	47.3 \pm 8.0	47.4 \pm 3.8

^a $n=11$ for PSP/no PSP condition; $n=14$ for SACM/no SACM condition; $n=6$ for both/neither condition.

^b $n=9$ for PSP/no PSP condition; $n=8$ for SACM/no SACM condition; $n=5$ for both/neither condition.

2.6. Statistics

A 2×6 analysis of variance (ANOVA) was used to investigate the effects of the individual factors on jump height. The independent variables used in the ANOVA were (1) the training level of the participants (two levels), and (2) the presence or absence of a PSP, SACM, or both simultaneously (six levels). The dependent variable was the maximum SJ height attained, as measured from the cable-extension transducer. Note that some participants did not exhibit a PSP or SACM on any of the jumps, therefore, not all subjects could be included in the analysis (refer to Table 2 for details). Also, note that only the vastus lateralis was used in the statistical analysis of the effects of a PSP on jump performance. The reason the EMG was taken from the antagonist muscle, the biceps femoris, was to verify that the silencing was not due to reciprocal inhibition causing a “false” silent period. An alpha level of 0.05 was used as the criterion for significance in all statistical procedures.

3. Results

The presence of a PSP, SACM, or both strategies simultaneously did not significantly increase jump height, in either the trained or the untrained individuals (Table 2). For all SJs, regardless of the occurrence of a PSP or SACM, the average jump height for the trained individuals (53.3 ± 7.7 cm) was significantly higher than for the untrained individuals (47.7 ± 4.1 cm).

Fig. 1 presents the total percent occurrence for both groups of participants, in trials with a PSP, trials with a SACM, and trials with both present simultaneously. There were no significant differences found between the groups.

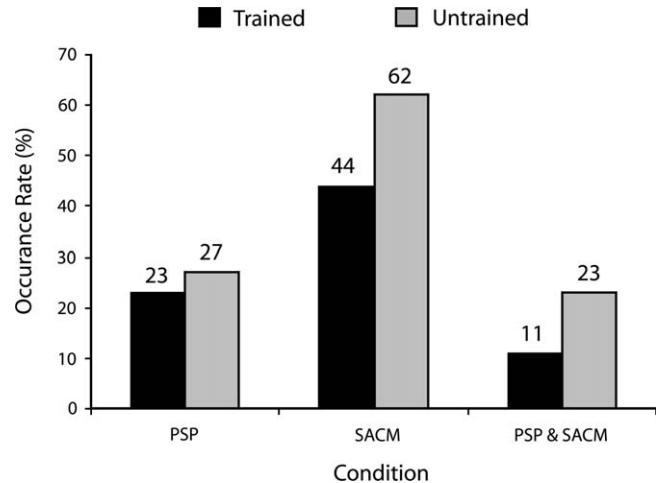


Fig. 1. Percentages of occurrence for the PSP, SACM, and both mechanisms appearing simultaneously, in trained and untrained participants.

Fig. 2 illustrates a typical individual dataset with both a PSP and a SACM present. In all participants, a PSP in the vastus lateralis was accompanied by a PSP in the biceps femoris. The duration of the silent period in the vastus lateralis was 40.4 ± 18.6 ms in the trained individuals and 34.6 ± 19.6 ms in the untrained individuals. A SACM in both the displacement and VGRF traces can also be observed in Fig. 2. The average magnitude of the SACM was 2.1 ± 1.3 cm in the trained individuals and 2.2 ± 1.2 cm in the untrained individuals. These displacements corresponded to an unloading of 109 ± 67 N in the trained individuals and 136 ± 88 N in the untrained individuals.

4. Discussion

The present study was designed to investigate two strategies used by the human body to increase the height of the SJ, in lieu of a large countermovement. The PSP and SACM were examined as possible facilitating mechanisms, however, they failed to significantly increase jump height. This was true for both unskilled jumpers and highly skilled jumpers.

As the PSP has been shown to be associated with increases in velocity and rate of force development in the literature [3,11,14,20], it was hypothesized that SJ height would be increased when a PSP was present. As this did not occur, it may be that the facilitatory effects of the PSP are present, but not of sufficient magnitude to yield a significant increase in jump height. These results are in line with the findings of Zehr et al. [23], who did not find significant facilitatory effects of the PSP in moderately trained karate practitioners and untrained individuals. Another factor that may have contributed to the findings is the highly variable nature of the PSP both between-subjects and within-subjects.

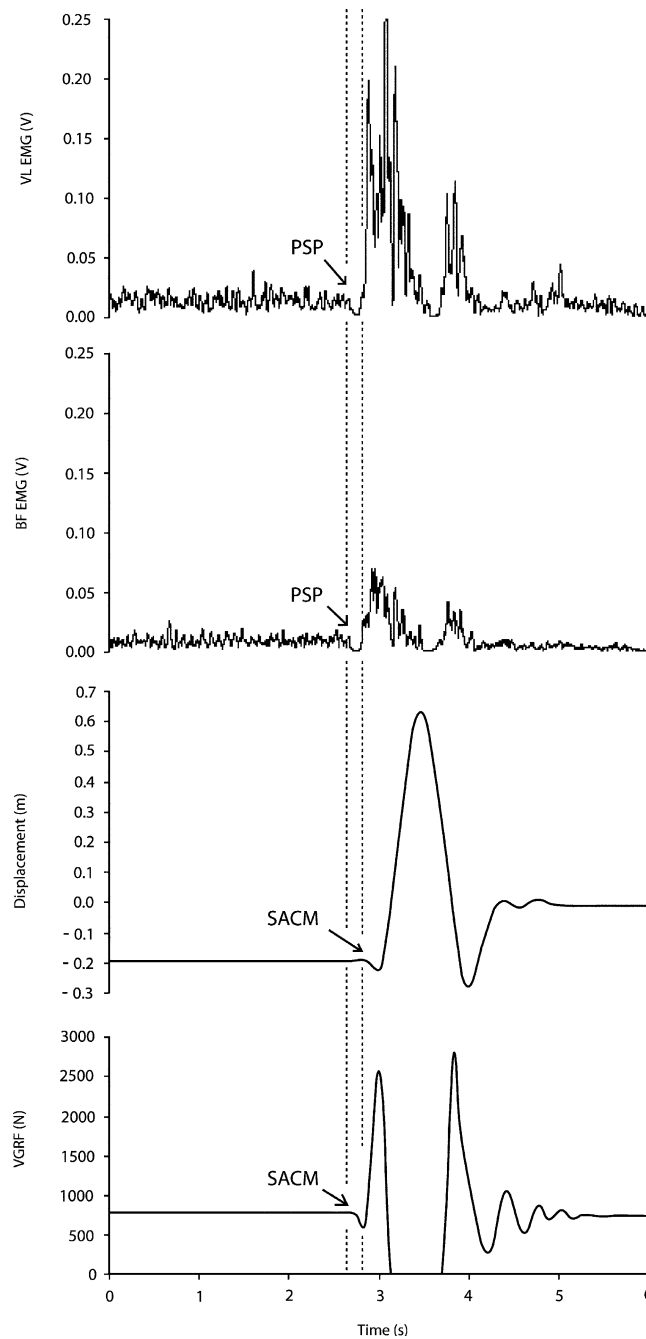


Fig. 2. A typical data set with both a PSP and SACM present. Top graph displays the rmsEMG of the vastus lateralis (VL). Graph second from the top displays the rmsEMG of the biceps femoris (BF). Third graph displays the smoothed displacement. Fourth and bottom graph displays the smoothed vertical ground reaction force (VGRF).

This variability is characteristic of the PSP, which has been present in the majority of past studies [15,23] and is a limitation in experiments. The findings of the present study, along with the results of previous research, suggest that the functional importance of the PSP is limited, but further investigation is warranted.

This study also found that the presence of a SACM does not increase the maximum height of SJs in either trained or untrained individuals. Previous evidence presented by Bosco et al. [8,9] suggested that SACMs may show positive effects on jump performance. However, in the present study, it was shown that SACMs of

about 1–3 cm did not increase the height of SJs significantly. This is valuable to future studies using the SJ. Researchers who have experienced difficulty with subjects performing SJs correctly (no countermovement) may be confident that their results reflect jumps that do not have facilitating mechanisms present, and that a SACM does not have an appreciable effect on performance.

Previous studies examining the PSP have taken great measures to make sure participants did not perform a countermovement prior to initiation of the motion. This has been enforced on some occasions, with a mechanical block to prevent back swing [20]. Along with this, displacement [20] and force [14] traces are often examined for the presence of a countermovement. These careful controls are imposed because a SACM may cause a “false” silent period, due to reciprocal inhibition from the antagonist muscle. In the present study, inhibition in the vastus lateralis was accompanied by inhibition in the biceps femoris (Fig. 2). This provides evidence against a PSP occurring in the agonist muscle due to reciprocal inhibition from the antagonist muscle.

It should be considered that the very nature of the PSP requires there to be a background level of force prior to silencing, or else there would be no electrical activity to silence. Therefore, when a muscle is producing tension to resist a load, the act of silencing will cause the limb to swing in the opposite direction. Even with a mechanical block present, it is possible for the muscle to lengthen as muscle activity terminates, contracting again to produce a very small stretch–shortening cycle. This is supported by results from Aoki et al. [3] who also suggested that the PSP causes the agonist muscle to be stretched by the external load being supported.

This leads one to hypothesize as to how a PSP can occur without a corresponding reduction in the VGRF. One possible answer was put forth by Moritani and Shibata [14]. The authors theorized that a silent period may occur without a corresponding force drop due to a phenomenon known as relaxation-electromechanical delay (R-EMD). This mechanism is similar to electromechanical delay (EMD), which is defined as the time period at the onset of muscle activity where an increase in force is not seen for a short time period (~20 ms) due to the stretching of the series-elastic component of the muscle-tendon complex [16].

In the study by Moritani and Shibata, it was demonstrated that when muscle activity terminates the force does not decrease instantaneously, but stays elevated for about 70 ms. This delay in the force response after muscle relaxation was referred to as R-EMD. Since the average duration of the PSPs in the present study (~40 ms) is shorter than the R-EMD duration (~70 ms), it is possible for a silent period to occur without a force drop. This is in excellent agreement with the results of

Moritani and Shibata, and offers an explanation as to why the PSP and the SACM did not occur simultaneously in 100% of the trials with the PSP present.

This study was done to examine the strategies used during the initiation of the SJ. It was proposed that, in the absence of a large countermovement, the body would use other strategies to increase performance. However, it was found that these strategies do not significantly affect the performance of the SJ. Researchers have assumed that a squat jump is purely concentric, and that there are no facilitating mechanisms that may influence the performance of the jump. This study provides evidence to support this assumption.

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