Kinematic and neuromuscular measures of intensity during plyometric jumps

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KINEMATIC AND NEUROMUSCULAR MEASURES OF INTENSITY DURING PLYOMETRIC JUMPS

ABSTRACT

The aim of this study was to assess jumping performance and neuromuscular activity in lower limb muscles after drop jumps (DJ) from different drop heights (*intensity)* and during continuous jumping (*fatigue*), using markers such as reactive strength, jump height, mechanical power and surface electromyography (sEMG). The eccentric (EC) and concentric (CON) sEMG from the medial gastrocnemius (MG), biceps femoris (BF) and rectus (R) muscles were assessed during all tests. In a cross-sectional, randomized study, eleven volleyball players (age 24.4±3.2 years) completed 20 to 90-cm (DJ20 to DJ90) drop jumps and a 60-s continuous jump test. A one-way ANOVA test was used for comparisons, with Sidak post-hoc. The α level was <0.05. Reactive strength was greater for DJ40 compared to DJ90 ($p<0.05$; ES: 1.27). Additionally jump height was greater for DJ40 and DJ60 compared to DJ20 ($p<0.05$; ES: 1.26 and 1.27, respectively). No clear pattern of neuromuscular activity appeared during DJ20 to DJ90: some muscles showed greater, lower, or no change with increasing heights for both agonist and antagonist muscles, as well as for eccentric and concentric activity. Mechanical power, but not reactive strength, was reduced in the 60-s jump test ($p<0.05$; ES: 3.46). No changes were observed in sEMG for any muscle during the eccentric phase nor for the R muscle during the concentric phase of the 60-s jump test. However, for both MG and BF, concentric sEMG was reduced during the 60-s jump test ($p<0.05$; ES: 5.10 and 4.61, respectively). In conclusion, jumping performance and neuromuscular markers are sensitive to DJ height (*intensity*), although not in a clear dose-response fashion. In addition, markers such as mechanical power and sEMG are especially sensitive to the effects of continuous jumping (*fatigue*). Therefore, increasing the drop height during DJ does not ensure a greater training intensity and a combination of different drop heights may be required to elicit adaptations.

KEY WORDS: explosive strength; muscle activation level; maximal voluntary contraction; jumping; plyometric training.

INTRODUCTION

Jumping performance may be critical to successful athletic performance in several sports, especially in those involving extensive jumping activity, such as volleyball (41). Plyometric exercises are often used to improve jumping ability in volleyball players (15, 32), by means of utilization of the stretch-shortening cycle (SSC) (37, 40). Drop jump (DJ) is a common plyometric drill (6, 39), especially among volleyball players (42). Drop jumps comprise a rapid transition between the eccentric and concentric muscle action (i.e., SSC) (27), allowing greater muscle activation and force (35). However, optimal implementation of DJs to promote muscle performance is inconclusive (12, 16, 36), especially regarding drop jump intensity.

Plyometric jump intensity is defined as the amount of stress placed on involved muscles and connective tissue and joints in the exercise (16). Commonly, athletes perform DJs at increased heights for a greater training-intensity stimulus (35). It has been suggested that intensity could be evaluated by examining a variety of kinematic parameters (e.g., jump height) and by assessing the activation of muscle by surface electromyography (sEMG) (18). Indeed, it has been shown that greater sEMG activity is apparent during DJs executed from a 60-cm box (DJ60) than from a 40-cm (DJ40) (7) or 20-cm box (DJ20) (35), suggesting greater plyometric jump intensity from greater drop heights. However, not all studies agree with these assertions (6, 18, 39). Moreover, although power output and reactive strength may augment with initial increases in drop box height, if drop height continues to increase the overall muscle performance may be negatively affected (21).

Although DJ is a common plyometric jump exercise, it usually requires the performance of an isolated jump followed by a recovery period. Therefore, neuromuscular fatigue [i.e., capacity to maintain a required or expected force and concomitant EMG level (14)] occurring during training and competition, which involve repetitive dynamic muscle actions (45), should be explored with drills other than an isolated DJ. This might be particularly important in volleyball, where players are called upon to complete multiple jumps during a game (43). Although some studies have assessed fatigue via EMG activity during dynamic movements (24, 45), including continuous jumping (11, 33) and slow and rapid SSC actions (44), if the results from such studies are replicable in highly trained volleyball players is a matter of further research. Such research should include neuromuscular and kinematic variables analyzed during the eccentric and concentric phases of muscles, both during agonistic and antagonistic actions. A better understanding of acute neuromuscular fatigue during repeated jumping may help to improve prescription of plyometric jump training.

Therefore, the aim of this study was to assess jumping performance and neuromuscular activity in lower limb muscles after DJ from different drop heights (*intensity)* and during continuous jumping (*fatigue*), using markers such as reactive strength, jump height, mechanical power and sEMG. We hypothesized that jumping performance and neuromuscular markers would be sensitive to DJ height (*intensity*) and continuous jumping (*fatigue*).

METHODS

Experimental approach to the problem

We performed a cross-sectional study to assess the effects of drop height during DJ (*intensity*) and duration (*fatigue)* on sEMG, reactive strength, jump height and mechanical power. Jumps were completed from 20, 30, 40, 50, 60, 70, 80 and 90-cm height boxes. To assess fatigue, a 60-s continuous jump test was completed.

Subjects

Eleven male college volleyball players (age, 24.4 ± 3.2 years; weight, 75.1 ± 13.1 kg; height, 1.79 ± 0.06 m; body mass index, 21.0 ± 3.3 kg/m^2) participated in this study. Athletes were recruited during the competitive period, where they usually complete one national-level competition per week. Body mass and height were measured using a calibrated electronic scale (HA-621 Tanita, Illinois, USA) and stadiometer (Butterfly, Shanghai, China), respectively. Subjects were enrolled if they did not report any lower extremity injury in the last 3 months before the time of testing. This was confirmed by checking their training logs with the team head coach. Athletes participated in their regular volleyball training sessions for three hours per day, three days per week, in the three months prior to inclusion in this study. The methods and procedures used were approved by the internal Ethical Committee of the responsible department for use of human subjects in experiments based on the Helsinki declaration (2008). An appropriate signed informed consent document was obtained from each subject before any of the tests were performed.

Procedures

In order to increase testing reliability, subjects were familiarized with test protocols during three one-hour sessions one week before measurements were undertaken (39). After familiarization, subjects completed a maximal voluntary isometric contraction (MVC) test on day one, a series of drop jump tests on day two and a 60-s continuous jump-fatigue test on day three. A standardized warm-up was completed before each testing day including 5 minutes of free running and 5 minutes of dynamic stretching (1). All tests were performed on the same surface that subjects regularly used to train and compete. The sEMG activity was recorded during each test and trial.

MVC. Subjects completed three squat (90-100° of knee angle) MVC trials in a power rack machine (PXLS-7930 Power Rack, Tuffstuff, Fitness International, USA), resting one minute between trials (17). The sEMG recorded during the best trial (i.e., maximal strength value) was used for analysis.

Drop jump tests. Three maximal DJ trials were randomly completed from 20, 30, 40, 50, 60, 70, 80 and 90-cm boxes (DJ20, DJ30, DJ40, DJ50, DJ60, DJ70, DJ80 and DJ90, respectively) (35). An electronic contact mat (Axon Jump 4.0, Bioengineering Sports, Argentina) was used to measure jump height (cm) and contact time (ms). Reactive strength index was calculated as height/contact time ($mm \cdot ms^{-1}$), as previously described (21, 36). Subjects jumped with arms akimbo and stepped off the box with the leading leg straight to avoid any initial upward propulsion during DJ execution. Upon landing, they were instructed to jump for maximal height and minimal contact time in order to maximize jump reactive strength (3). The reliability and validity of this protocol have previously been determined (36). Subjects had 30 seconds of rest between jumps and 60 seconds between heights. The best performance trial (higher reactive strength index value) was used for statistical analysis.

Continuous jump test. A continuous 60-s jump test was performed as previously described (8). Subjects were verbally instructed to “jump as high as you can, with minimum ground contact time”, with no restriction on the knee joint angle. Jump height, contact time and reactive strength were measured as described in the previous paragraph. Mechanical power was calculated as previously described ($W \cdot kg^{-1}$) (8, 10):

$$W = \frac{g^2 \cdot Tf \cdot Tt}{4 \cdot n \cdot (Tt - Tf)}$$

where g = acceleration of gravity ($9.81 m/s^2$); Tf = mean flight time; Tt = total time; n = n° of jumps. The mechanical power in the 60-s jump test correlate well with the Wingate test (8). Dependent variables were continually measured and comparisons were made at 1–15, 15–30, 30–45 and 45–60-second intervals. Given the maximal-effort and fatigue effects of this test, subjects performed only one maximal attempt. Therefore, reliability was not estimated.

Surface Electromyography. The sEMG data was used to quantify muscle activity using a three-channel shielded cable (Biopac, model MP150). After warm up the skin was carefully shaved, abraded and cleansed with alcohol prior to application of sEMG bipolar electrodes (Ag-AgCl, 4.0 x 3.2 cm, 3M Health Care, Canada). The electrodes were placed on the muscle belly surface of the rectus femoris (R), medial gastrocnemius (MG) and biceps femoris (BF) muscles of the dominant leg. The electrodes and wires were secured with adhesive tape (3M, Canada). The sEMG signals from each electrode were amplified (input impedance 120 kΩ; signal to noise ratio 0.2 µV; inter-electrode distance of 10 mm) (18) and gain range of 500 to 5000. Surface electrodes were connected to an amplifier EMG100C unit (Biopac System, Goleta, CA) and streamed continuously through an analog to digital converter to a computer (G-42, HP notebook computer, USA). The sEMG data was managed with computer software (AcqKnowledge 4.1; Biopac Systems, Inc.). All data were filtered with a 10-Hz high-pass and a 500-Hz low-pass filter.

EMG data recording. The root mean square (RMS) was used to assess sEMG recorded during jump testing (18, 24, 29). Data were calculated using a 60-ms moving window. Data were analyzed to identify the pre- and post-contact muscle burst timing and the magnitude of action for the jump (17). The RMS was evaluated as previously suggested (24):

$$RMS = \sqrt{\frac{1}{n}\sum_{n} x_{n}^{2}}$$

where X_n is the value of the sEMG signal and n is the sample number. During jump testing the eccentric (EC) and concentric (CON) EMG activity was recorded, coupled with a digital video camera to detect each phase (Microsoft, LifeCam Studio HD). From these recordings, EC/CON ratio was calculated. Each RMS sEMG data was expressed as a percentage of MVC (38, 46). The reliability of these measures has previously been established (18).

Statistical Analysis

Data are presented as mean ± standard error of the mean (SEM). The Shapiro Wilk and Levene tests, respectively analyzed the normality and homoscedasticity of the outcome variables. A one-way ANOVA test was used to compare dependent variables collected during the drop jump tests and during the 60-s continuous jump test. When a significant F value was achieved, Sidak two tails post-hoc procedures were performed to locate the pairwise differences between the means. The α level used for all statistics was <0.05. We calculate the effect size (ES) and statistical power (SP) for each comparison (G*Power, Version 3.1.9.2, Germany, Düsseldorf) (20). Threshold values for ES were 0.20, 0.60, 1.2, and 2.0 for small, moderate, large, and very large, respectively (28). All statistical calculations were performed using STATISTICA Software (Version 8.0, StatSoft, Inc, Tulsa, Oklahoma, USA).

RESULTS

Drop jump tests

Reactive strength was 24.9% greater in DJ40 compared to DJ90 ($p<0.05$; ES: 1.27; SP: 90%). Jump height was 12.4 and 13.8% greater from DJ40 vs. DJ20 ($p<0.05$; ES: 1.26; SP: 90%) and DJ60 vs. DJ20 ($p<0.05$; ES: 1.27; SP: 91%), respectively (Table 1).

Table 1. Determination of plyometric exercise intensity using reactive strength, jump height and surface electromyography (% MVC) from different drop height.

	DJ20	DJ30	DJ40	DJ50	DJ60	DJ70	DJ80	DJ90	
Reactive strength (mm/ms)	1.58 ± 0.2	1.64 ± 0.1	1.93 ± 0.2	1.68 ± 0.1	1.90 ± 0.1	1.71 ± 0.1	1.63 ± 0.1	1.45 ± 0.1$^{\beta}$	P<0.05
Jump height (cm)	27.7 ± 1.5	31.1 ± 1.7	36.4 ± 2.3*	33.1 ± 1.9	37.0 ± 2.4*	33.6 ± 1.8	33.6 ± 1.8	31.9 ± 1.6	P<0.05
MG EC (%MVC)	72.0 ± 6.2	76.7 ± 6.2	91.3 ± 5.2	89.9 ± 6.6	75.4 ± 2.5	70.9 ± 2.1	69.9 ± 3.4	66.8 ± 4.6$^{\beta}$	P<0.05
MG CON (%MVC)	67.6 ± 5.3	70.8 ± 4.7	77.7 ± 6.1	66.3 ± 5.0	92.1 ± 4.1*$^{\gamma}$	83.4 ± 5.8	97.9 ± 4.8*$^{\alpha\gamma}$	82.5 ± 3.2	P<0.05
BF EC (%MVC)	79.5 ± 7.9	98.3 ± 8.8	99.4 ± 9.3	106 ± 8.6	80.6 ± 6.6	97.4 ± 8.9	69.9 ± 2.2	98.1 ± 5.1	NS
BF CON (%MVC)	112 ± 11.6	80.0 ± 7.8	75.7 ± 5.6	62.8 ± 6.4*	95.8 ± 6.8	89.4 ± 9.3	89.0 ± 5.8	76.8 ± 6.3	P<0.05
R EC (%MVC)	79.8 ± 7.4	120 ± 14.3	130 ± 16.6	131 ± 14.5	150 ± 19.9	156 ± 14.0*	113 ± 16.4	155 ± 13.2*	P<0.05
R CON (%MVC)	136 ± 14.4	137 ± 13.2	146 ± 14.5	129 ± 18.1	175 ± 16.7	165 ± 19.6	188 ± 18.8	168 ± 17.8	NS
MG EC/CON ratio	1.14 ± 0.2	1.13 ± 0.1	1.26 ± 0.2	1.53 ± 0.2	0.84 ± 0.1$^{\gamma}$	0.89 ± 0.2	0.75 ± 0.1$^{\gamma}$	0.86 ± 0.1$^{\gamma}$	P<0.05
BF EC/CON ratio	0.72 ± 0.1$^{\gamma}$	1.26 ± 0.1	1.26 ± 0.1	1.66 ± 0.2	0.83 ± 0.1$^{\gamma}$	1.07 ± 0.1	0.83 ± 0.2$^{\gamma}$	1.34 ± 0.2	P<0.05
R EC/CON ratio	0.64 ± 0.1	1.03 ± 0.1	0.99 ± 0.3	1.29 ± 0.2	0.92 ± 0.1	1.15 ± 0.1	0.62 ± 0.1	1.18 ± 0.2	NS

Data are mean ± SEM. MG: medial gastrocnemius; BF: biceps femoris; R: rectus; MVC: maximal voluntary contraction; EC: eccentric; CON: concentric; DJ20, DJ30, DJ40, DJ50, DJ60, DJ70, DJ80, DJ90: drop jump from 20-cm to 90-cm, respectively. *: significantly different *vs*. DJ20. $^{\alpha}$: significantly different *vs*. DJ30. $^{\beta}$: significantly different *vs*. DJ40. $^{\gamma}$: significantly different *vs*. DJ50.

Regarding eccentric sEMG, MG activation was greater in DJ40 than DJ90 (26.8%; $p<0.05$; ES: 4.97; SP: 99%). In the R muscle, activation was greater in DJ70 vs. DJ20 (49.0%; $p<0.05$; ES: 6.28; SP: 99%) and DJ90 vs. DJ20 (48.7%; $p<0.05$; ES: 6.56; SP: 99%). R sEMG did not change across DJ heights.

Regarding concentric sEMG, MG activity was greater in DJ60 vs. DJ20 (26.6%; $p<0.05$; ES: 5.08; SP: 99%), DJ80 vs. DJ20 (31.0%; $p<0.05$; ES: 5.97; SP: 99%), DJ60 vs. DJ50 (28.0%; $p<0.05$; ES: 5.21; SP: 99%) and DJ80 vs. DJ50 (27.7%; $p<0.05$; ES: 6.09; SP: 99%). In BF activity was greater in DJ20 than DJ50 (43.7%; $p<0.05$; ES: 4.88; SP: 99%). BF, EC, and R CON showed similar sEMG during all DJs (Table 1).

Regarding EC/CON sEMG ratio, MG ratio was greater in DJ50 than DJ60 (46.7%; $p<0.05$; ES: 3.98; SP: 98%), DJ50 vs. DJ80 (53.3%; $p<0.05$; ES: 4.50; SP: 99%) and DJ50 vs. DJ90 (40%; $p<0.05$; ES: 3.86; SP: 97%). BF ratio was greater in DJ50 than DJ20 (58.8%; $p<0.05$; ES: 5.42; SP: 99%), DJ50 vs. DJ60 (52.9%; $p<0.05$; ES: 5.43; SP: 99%) and DJ50 vs. DJ80 (52.9%; $p<0.05$; ES: 4.15; SP: 98%). R ratio was similar across DJ heights (Table 1).

Continuous jump test

Although reactive strength index and mechanical power were similarly reduced during the 60-s jump test, only mechanical power was significantly reduced (22.1 ± 2.2 vs. 14.8 ± 2.0 $\mathrm{W \cdot kg^{-1}}$, 0–15 vs. 45–60 interval, respectively; $p<0.05$; ES: 3.46; SP: 0.99%, Figure 1).

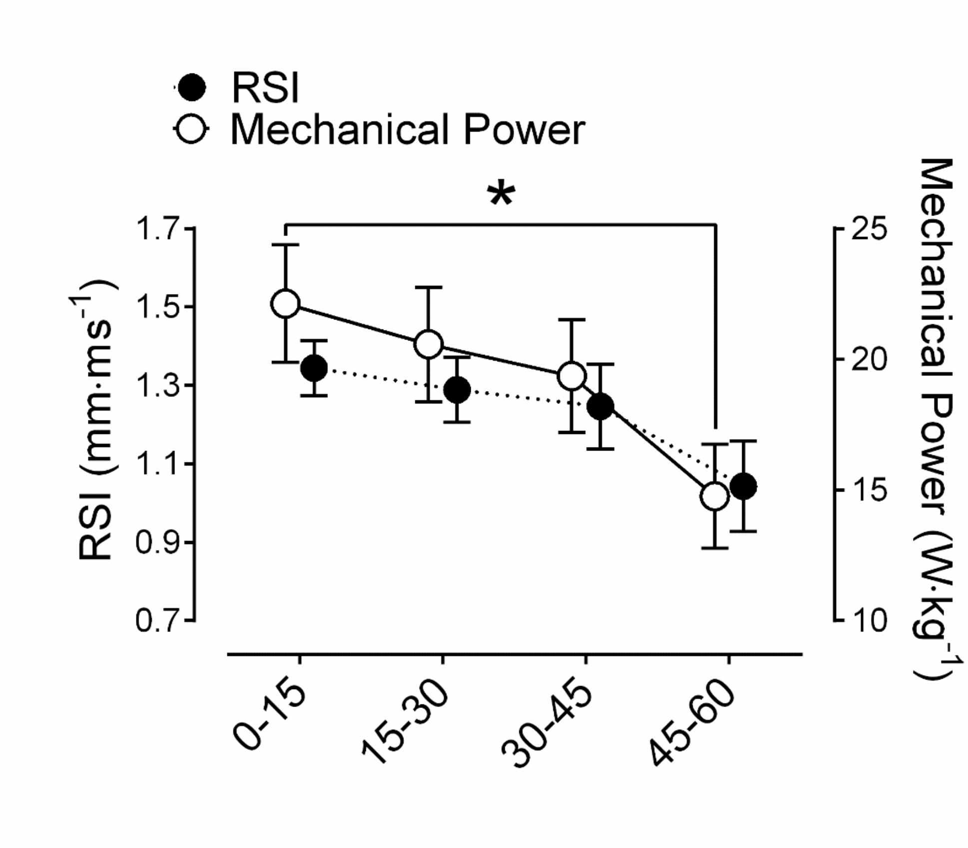

Figure 1. Reactive strength index (RSI) and mechanical power in volleyball athletes (n=11) during a 60-s continuous jump test. The mechanical power was significantly reduced in 45-60 vs. 0-15-s interval. The RSI reduction was not significant. One way ANOVA, following Sidak post-hoc, *, $p<0.05$ vs. 0-15-s, n=11.

No changes were observed in sEMG for any muscle during the eccentric phase, nor for the R muscle during the concentric phase of the 60-s jump test (Figure 2). However, both MG and BF concentric sEMG activity were reduced during the fatigue test. In MG, compared to 0-15 s (74.6 ± 6.6 %MVC), the reduction occurred at 30-45 s (48.6 ± 5.9 %MVC; $p<0.05$; ES: 4.14; SP: 0.98%) and 45-60 s (44.9 ± 4.4 %MVC; $p<0.05$; ES: 5.10; SP: 0.99%) (Figure 2A). In BF, compared to 0-15 s (84.9 ± 11.5 %MVC), the reduction occurred at 15-30 s (59.4 ± 9.1 %MVC; $p<0.05$; ES: 2.45; SP: 0.97%), 30-45 s

(45.7 ± 6.0 %MVC; $p<0.05$; ES: 4.27; SP: 0.99%) and 45-60 s (44.5 ± 4.6 %MVC; $p<0.05$; ES: 4.61; SP: 0.99%) (Figure 2C). No significant changes were observed in the EC/CON sEMG ratio for any muscle during the 60-s jump test (Figure 2B, D and F).

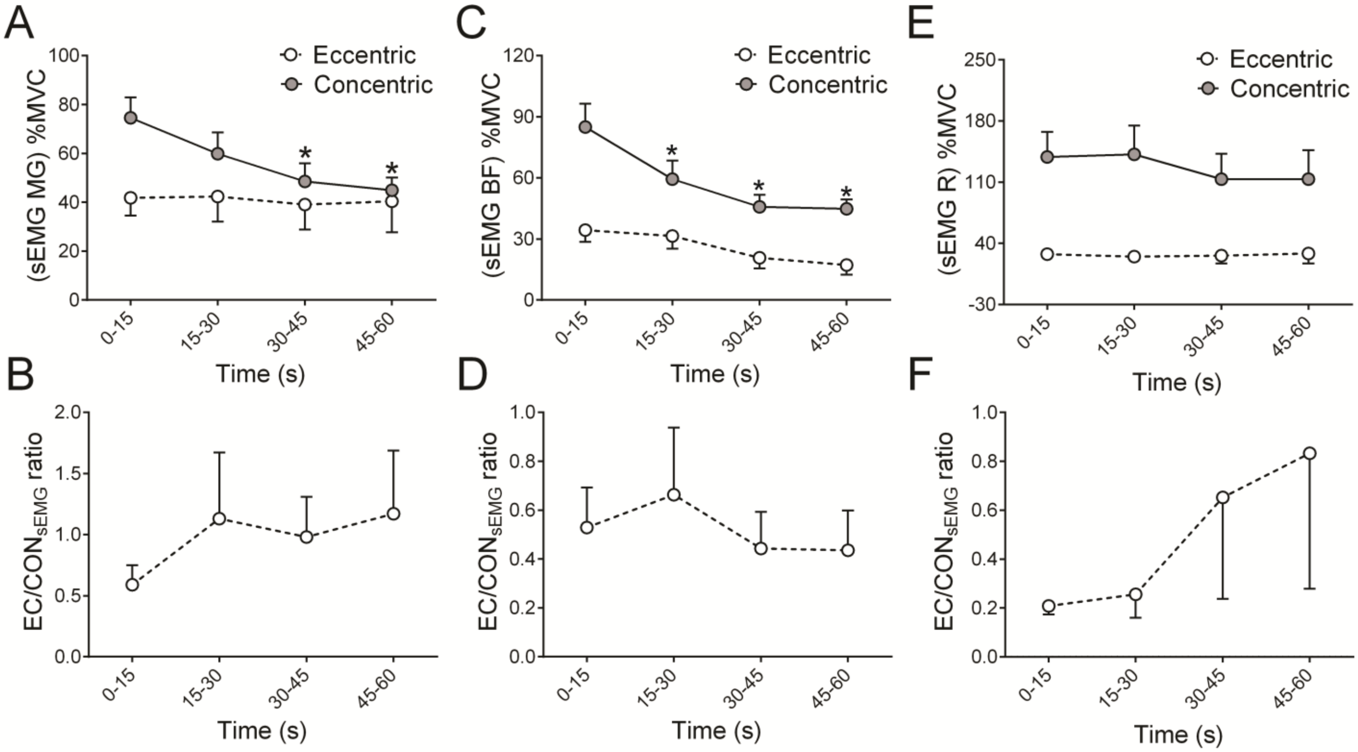

Figure 2. Surface electromyography (sEMG) in volleyball athletes during a 60-s continuous jump test. (A) sEMG for medial gastrocnemius (MG) concentric (CON) phase was significantly reduced in 30-45 and 45-60-s compared to the 0-15-s interval time. Note that the eccentric (EC) phase was not change in all intervals. (B) EC to CON sEMG ratio was not different between all intervals. However, note that the EC contribution is slightly increased in the 60-s continuous jump test. (C) Biceps femoris (BF) sEMG CON phase was significantly different in 0-15 vs. 15-30; 30-45; and 45-60-s interval time, without significant differences in EC phase. (D) EC to CON sEMG ratio was not different between all intervals. (E) sEMG for rectus (R) were not different in all test for both, CON and EC muscle contraction phase,

and for EC/CON$_{sEMG}$ ratio (F). Data are expressed as a % of maximal voluntary contraction (MVC). One way ANOVA, following Sidak post-hoc *, $p<0.05$ vs. 0-15 s, n=11. Note: the standard error of the mean values are shown only to one side, either negative or positive, for a clear graphical presentation.

DISCUSSION

The aim of this study was to assess jumping performance and neuromuscular activity in lower limb muscles after DJs from different drop heights (*intensity)* and during continuous jumping (*fatigue*), using markers such as reactive strength, jump height, mechanical power and sEMG. In general, a greater RSI and jump height was registered from moderate drop jump heights (40 and 60 cm boxes). Regarding sEMG, no clear pattern of activation emerged according to drop jump height, with greater MG activation from DJ40 (eccentric) as well as from DJ60 and DJ80 (concentric), greater BF activation from DJ20 (concentric) and greater R activation from DJ70 and DJ90 (eccentric). Therefore, it is debatable if a greater DJ drop height is indicative of greater *intensity*. In this sense, the intensity imposed by a given drop height will vary according to muscle type and its specific action during jumping. Regarding the fatigue challenge imposed by the 60-s continuous jump test, mechanical power and concentric sEMG showed sensitivity to the test. Reactive strength, eccentric and EC/CON$_{sEMG}$ ratio showed no sensitivity to the test. Although the EC to the CON sEMG ratio was not sensitive to performance changes during the 60-s continuous jump test, it demonstrated sensitivity during DJ from different heights.

Drop jump tests

Reactive strength was greater in DJ40 compared to DJ90, and jump height was greater from DJ40 and DJ60 compared to DJ20 (Table 1). The greater performance from DJ40 and DJ60 may be related to greater motor unit recruitment (14), possible due to optimal eccentric forces (19). In this sense, *too low* or *too high* drop jump heights may not correspond to optimal heights, reducing muscle activation (18). However, a greater kinematic performance may not necessarily coincide with peaks of sEMG activity

(Table 1). This might be explained by the interaction between contractile elements and series elastic elements (5), independent from electrical activity. In this sense, reutilization of elastic energy (39) might have contributed to performance enhancement. Alternatively, reduced performance from higher DJ drop heights might be related to neuromuscular inhibition, which serves as a protective strategy to prevent muscle and tendon injury from excessive stress in the muscle-tendon unit (30, 39). Such inhibition might be related to strength level (18) or landing mechanics.

Although no consensus exists (18, 35), these results agree with the notion that moderate drop heights during DJ allow maximization of performance (35). An additional explanation for the discrepancy in the literature might be related to the different methodologies used to assess kinematic and neuromuscular markers (17, 18, 23). In the present study, sEMG activity was normalized to MVC to compensate for differences in strength, muscle tone, fat mass and muscle geometry among other factors that may induce bias in the results (2).

Regarding eccentric muscle activity, greater sEMG was observed in the MG from DJ40 and in the R from DJ70 and DJ90. However, the BF muscle showed similar activity between all drop heights. These results suggest that compared to the agonist muscles, motor unit recruitment from antagonist muscles, such as the BF, manifest differently (may not change) during the eccentric phase when different DJ heights are used. This agrees with previous findings (26, 35). In relation to concentric muscle activity, MG activity was greater in DJ60 than DJ20 and DJ50, and in DJ80 than DJ20, DJ30 and DJ50. In the BF muscle, greater activity was observed in DJ20 than DJ50. The R muscle showed similar activity during the concentric phase between all DJ heights, contrasting with previous reports (35). Regarding EC/CON sEMG ratio, MG and BF showed a greater ratio at DJ50, although R ratio was similar between all DJ heights. This proportionally greater increase of eccentric over concentric activity toward DJ50 coincides with greater reactive strength from DJ40 and jump height from DJ40 and DJ60. In this sense, EC/CON sEMG ratio might be better suited to assessing jump kinematics than isolated concentric or eccentric sEMG.

Taken together, our results suggest that motor unit recruitment changes across DJ heights during the eccentric and concentric phases, with a different pattern of change across agonist and antagonist muscles. From a practical perspective, it may be advisable for coaches to incorporate different drop heights during training in a periodized fashion according to athletes’ specific needs during the season.

Continuous jump test

Although mechanical power and concentric sEMG (MG and BF) were reduced during the test, subjects maintained a consistent performance on RSI, eccentric sEMG and EC/CON sEMG. Sustaining reactive strength and eccentric muscle activation during repeated jumping may be a particular trait of volleyball players due to the need to cope with a high number of repeated jumps during matches (22). Maintenance of eccentric sEMG of agonist/antagonist muscles during repeated jumping activity may not only help to maintain reactive strength performance but also may reduce injury risk during eccentric landing. This is because impact forces may be as high as 11 times subject´s body weight (34).

It seems that some particular markers may be more sensitive to changes occurring during muscular effort (4). In this sense, mechanical power and concentric muscle sEMG might better reflect fatigue-related phenomena occurring during continuous jumping thus being more suitable as markers to assess fatigue-resistance capacity. Moreover, declines in concentric sEMG occur earlier than mechanical power, indicating a potentially greater sensitivity of sEMG to detect early-onset physiological alterations (e.g., lower recruitment of motor units (9, 13)). Alternatively, it may be that mechanical performance depends on factors others than motor unit recruitment, as suggested by muscle force maintenance while sEMG diminished during submaximal exercise (31). Future research should clarify this issue comparing mechanical power, sEMG and other potentially relevant neuromechanical markers, that may be relevant not only from a performance point of view but also for injury prevention (4).

In conclusion, jumping performance and neuromuscular markers are sensitive to DJ height (*intensity*), although not in a clear dose-response fashion. In addition, markers such as mechanical power and sEMG are especially sensitive to the effects of continuous jumping (*fatigue*).

PRACTICAL APPLICATIONS

Training intensity is a key variable to consider in exercise prescription. Although some forms of strength training (e.g., resistance training) have precise ways of quantifying intensity (e.g., %1RM), plyometric training lacks these markers. Although anecdotal recommendations have been provided to classify plyometric jump training drills (e.g., drop height), based on the current results it is clear that drop height during DJ is not a clear marker of intensity. Although potentially useful, sEMG-based intensity prescription should take into account the muscle group and its action (concentric, eccentric).

It might be that instructions usually provided to athletes (e.g., "jump as high and fast as you can") during regular training sessions offer more insight regarding the intensity of a jump. It could therefore be argued that the intention to perform a jump maximally is more important than the height of the jump itself, a similar concept to what other authors have noted for resistance training (25). In addition, in line with basic training principles (e.g., variation; periodization, individualization) it is recommended that coaches use different drop heights to stimulate adaptations in their athletes.

Regarding neuromuscular fatigue during continuous jumping, it seems that some markers (i.e., mechanical power; sEMG) are more sensitive to this type of activity. Thus, such markers may have greater potential to assess athletes' muscle fatigue resistance during a pattern of activity that mimics the numerous number of jumps completed during training and competition. However, eccentric muscle activity was not affected by repeated jumping. This was in line with the maintenance of reactive strength during the test. It may be that athletes had an adequate level of preparedness to support the impact forces of repeated eccentric landings. In this sense, the assessment of an athlete's capacity to maintain eccentric activity (and reactive strength) during repeated jumping might also be a relevant parameter. In addition, it may be relevant for coaches to assess athlete's ability to maintain adequate landing mechanics during repeated jumping.

Practitioners should take into account that according to the drop jump height and jump duration used during training, the behavior of jumping performance and lower limbs' neuromuscular markers may change, also depending on the muscle function (e.g., agonist; antagonist) and action (i.e., eccentric; concentric) during jump drills. Future research should clarify the implications of these variations for training prescription.

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FIGURE LEGEND

Figure 1. Reactive strength index (RSI) and mechanical power in volleyball athletes (n=11) during a 60-s continuous jump test. The mechanical power was significantly reduced in 45-60 vs. 0-15-s interval. The RSI reduction was not significant. One way ANOVA, following Sidak post-hoc, *, $p<0.05$ vs. 0-15-s, n=11.

Figure 2. Surface electromyography (sEMG) in volleyball athletes during a 60-s continuous jump test. (A) sEMG for medial gastrocnemius (MG) concentric (CON) phase was significantly reduced in 30-45 and 45-60-s compared to the 0-15-s interval time. Note that the eccentric (EC) phase was not change in all intervals. (B) EC to CON sEMG ratio was not different between all intervals. However, note that the EC contribution is slightly increased in the 60-s continuous jump test. (C) Biceps femoris (BF) sEMG CON phase was significantly different in 0-15 vs. 15-30; 30-45; and 45-60-s interval time, without significant differences in EC phase. (D) EC to CON sEMG ratio was not different between all intervals. (E) sEMG for rectus (R) were not different in all test for both, CON and EC muscle contraction phase, and for EC/CON_{sEMG} ratio (F). Data are expressed as a % of maximal voluntary contraction (MVC). One

way ANOVA, following Sidak post-hoc *, $p<0.05$ vs. 0-15 s, n=11. Note: the standard error of the mean values are shown only to one side, either negative or positive, for a clear graphical presentation.