

Effect of squat depth on performance and biomechanical parameters of countermovement vertical jump

A influência da profundidade de agachamento no desempenho e em parâmetros biomecânicos do salto com contra movimento

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Abstract – The aim of this study was to analyze the effect of different squat depths in the performance and biomechanical parameters at counter movement jump (CMJ). Twenty-two male volleyball or basketball players volunteered to participate in this study and all were currently competing at the college level. The CMJ was performed in three different conditions: 1) with relative knee flexion at the end of counter movement phase smaller than 90° (<90°); 2) greater than 90° (>90°), and; 3) preferred position (PREF). During the CMJ, kinematic, kinetic, and electromyography parameters were assessed. ANOVA for repeated measures with post-hoc Bonferroni's test was used for variables comparison, with a significance level set at $p \leq 0.05$. The higher performance was on PREF and <90° situations compared with CMJ>90°. Average and peak power, as well as absolute and normalized peak forces, were higher in >90° CMJ. The peak velocity of CG and angular velocities of hip and knee were higher in the <90° condition. EMG activity of the vastus lateralis (VL) during the descending and ascending phases were higher in position >90°. Rectus femoris and biceps femoris did not show difference in any jump phases. In conclusion, the knee flexion interferes the performance and the biomechanical variables at the CMJ. The highest jumps were got at a deeper squat, so this technique could be used for athletes in order to optimize the vertical jump performance in the training and competitions.

Key words: Stretch-shortening cycle; Vertical jump.

Resumo – O objetivo do presente estudo foi analisar a influência de diferentes profundidades de agachamento no desempenho e em parâmetros biomecânicos no salto com contra movimento (CMJ). Participaram do estudo 22 atletas de voleibol ou basquetebol do sexo masculino, participantes de competições em nível regional e universitário. Os CMJ foram realizados em três condições: 1) com flexão relativa do joelho ao final da fase de contra movimento menor que 90° (CMJ<90°); 2) maior que 90° (CMJ>90°) e; 3) posição preferida (CMJ_{PREF}). Durante os CMJ foram mensurados: altura do salto, variáveis cinemáticas, cinéticas e eletromiográficas. ANOVA para medidas repetidas com post-hoc de Bonferroni foi utilizado na comparação das variáveis, adotando-se nível de significância de $p \leq 0,05$. O desempenho foi maior na situação PREF e <90° comparado ao CMJ >90°. A potência média e pico, a força máxima normalizada e absoluta, apresentaram os maiores valores na posição >90°. O pico de velocidade e as velocidades angulares de quadril e joelho apresentaram os maiores valores na posição <90°. A EMG do vasto lateral, durante as fases descendente e ascendente, foi maior na posição >90°. Os músculos reto femoral e bíceps braquial não apresentaram diferença entre as condições. Conclui-se que o desempenho e as variáveis biomecânicas analisadas no CMJ são influenciados pelo nível de flexão do joelho. As maiores alturas foram obtidas nos saltos realizados a partir de uma maior profundidade de agachamento, assim, tal estratégia técnica poderia ser utilizada por atletas a fim de otimizar a altura do salto vertical nos treinamentos e competições.

Palavras-chave: Ciclo alongamento-encurtamento; Desempenho; Salto vertical.

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INTRODUCTION

Vertical jump has been one of the tests most used by coaches and researchers to assess the muscle power of the lower limbs of athletes from different sport modalities¹⁻². In addition, vertical jump is a motor skill performed in several sports during movements like attacking and blocking in volleyball, rebound in basketball, among others.

Aimed at maximizing performance during vertical jump, athletes usually take a specific and preferred initial posture, in case of jumping from a static position or performing a certain squatting extent on countermovement jumps (CMJ). According to Zatsiorsky³, the arrangement of body segments or adjustments of joint angles during motor actions defines a particular muscle length. In the case of vertical jump, the modulation of the level of knee flexion, in other words, the magnitude of squat preceding jump and hip movement change the length of thigh muscles. These segmental movements will reflect in changes in the length-tension relationship and consequently in the generation of impulse⁴. According to the theory of cross bridges⁶, there seems to be an “optimum” muscle length for force production. When the muscle fibers are much shortened or elongated reductions in force production may be observed because there is less interaction between cross bridges⁶.

Some authors⁷⁻⁹ have reported that the squat depth influences the height reached in the vertical jump, although divergent results are found in literature¹⁰. In addition, changes are also observed in important jump performance predictors such as strength, power and impulse⁷⁻⁸. According to these authors, strength and power seem to have larger magnitudes in vertical jump when performed at small squat depths. On the other hand, greater impulse is observed in jumps performed from greater squat depths due to increased time of force application⁸. Thus, it is necessary to understand in which situations of body adjustment it is possible to maximize jump height.

Additionally, changes in EMG activation may be due to modulations in muscle recruitment and performance of elastic components in these different body adjustments¹¹⁻¹². However, studies have shown some inconsistent results regarding this aspect. Bobbert et al.⁹ found no difference in EMG activation in any of the lower limb muscles analyzed during vertical jump performed at different levels of knee flexion. Sales et al.¹³ have found greater EMG activation of gastrocnemius, vastus lateralis and gluteus maximus muscles in jumps performed at 90° of knee flexion compared to lower squat depth positions (50° and 70°). One aspect still under discussion in literature is about biarticular muscles, which for playing a biarticular role in knee and hip during vertical jump, may not present a substantial change in its length in jumps performed at different knee flexion angles and thus not modify the EMG activity pattern.

Investigations have shown inconsistencies with regard to the identification of joint positions or amplitudes (mainly knee and hip) that enable

maximizing performance in vertical jump as well as which biomechanical variables are modulated in these situations that can explain performance. In this context, this study aimed to analyze performance, EMG activity of muscles of the lower limbs, and kinetic and kinematic parameters during countermovement jump (CMJ) performed from different squat depths. The main hypothesis of the study is that the best performance on CMJ is obtained in situations performed from higher squat depth positions.

METHODOLOGICAL PROCEDURES

Subject

The study included 22 male subjects, volleyball or basketball players, with the following characteristics (mean \pm SD): 23.5 \pm 3.6 years; 82.4 \pm 9.8 kg; 185.5 \pm 6.3 cm; 13.8 \pm 3.3% fat; 4.8 \pm 2.5 years of systematic practice in the sport. Subjects participated in regional and university competitions. The criteria used for the selection of participants were: a) to participate in sport in which vertical jump was part of the game action (volleyball, basketball, handball, etc.); b) to have minimum of one year of practice in the sport; c) minimum frequency of training of twice a week and; d) do not have any type of injury that prevented the performance of evaluations.

Participants were first informed about the study objectives and then signed the informed consent form. The study was approved by the Ethics Committee on Human Research of the UFSC under number 01832712.0.0000.0121.

Study design

Participants attended the laboratory on two days. On the first visit, anthropometric measurements and familiarization with CMJ in three different squat depths were performed. The second visit was aimed at data collection. On this day, participants initially performed a warm-up exercise consisting of static stretching with emphasis on the lower limbs, five minutes of pedaling on a cycle ergometer at 50 watts, two sets of 10 hops continuously and five to six submaximal CMJ.

CMJ Protocol

To perform CMJ, the individual started from a standing position with hands on the hips. From this, the individual should perform a countermovement (descending or negative phase) followed by a rapid extension of the lower limb joints (ascending or positive phase). The athlete was asked to perform jumps from three different conditions of relative maximum knee flexion, always measured at the end of the descending phase: 1) less than 90° (CMJ<90°); 2) greater than 90° (CMJ>90°); 3) self-selected, called preferred position (CMJ_{PREF}) (Figure 1). Subjects were requested to keep trunk as vertical as possible during jumps to minimize the effects on performance

The control of these positions was conducted via subjective perception of the subject trained during familiarization. In this session, knee flexion angle

of 90° was initially set, measured in static mode using a goniometer, which was considered reference by athletes. After this, participants were requested to perform several CMJ attempts flexing knees in the descending phase of the jump beyond this angle (<90°) and other attempts flexing less than 90° (>90°). Attempts were analyzed by the evaluator who proposed possible adjustments.

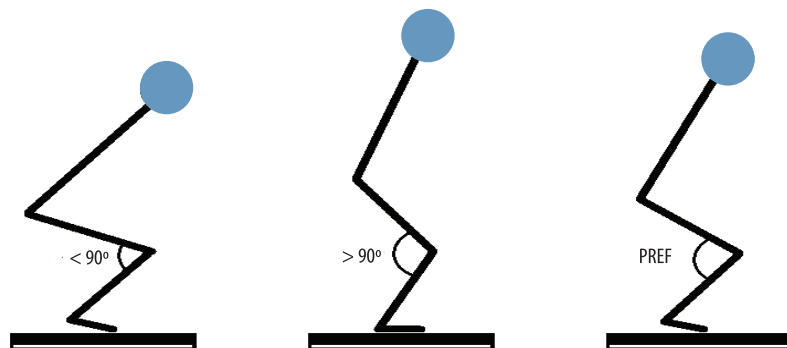


Figure 1. Schematic illustration of the three situations tested in CMJ.

The values obtained via kinematic analysis of relative knee (K) and hip angles (H) at CMJ<90° (K = 73.1 ± 6.29°, H = 50.0 ± 12.34°), CMJ>90° (K = 98.4 ± 4.81°, H = 92.0 ± 14.31°) and CMJ_{PREF} (K = 84.9 ± 6.81°, H = 68.1 ± 9.35°) indicated that the positioning control was effective. Three attempts were made in each situation tested, with one-minute intervals and in random execution order. During jumps, kinematic, kinetic and electromyographic variables were measured.

Kinematic analysis

A two-dimensional videography of motion in the sagittal plane using a digital camera (Canon ELPH 500HS) with acquisition frequency of 120 Hz was performed. The camera was positioned on a tripod at a distance of five meters from the participant and 1 m from ground level. Reflective markers were fixed on the following anatomical references: fifth metatarsal of the head, lateral malleolus, lateral femoral epicondyle, greater trochanter of femur and acromion (right side).

The video was digitalized using the Video 4 Coach software – Skill Spector version 1.2.4. Raw data were filtered with 4th order low-pass Butterworth filter with cut-off frequency of 6 Hz, determined from spectral analysis. From the digitization of images, a two-dimensional reconstruction of motion was performed, yielding trunk, thigh, leg and foot segments. The following variables were calculated: a) relative angles (degrees) of hip (between trunk and thigh segments), knee (between thigh and leg segments) and ankle (between leg and foot segments); b) angular velocities (°/s) of the respective joints derived from the derivation of the angular position versus time. These variables were obtained at the moment of transition between the descending and ascending phases of the jump, identified by the vertical displacement of the anatomical reference of the greater trochanter. A routine developed in MatLab® version 7.9.0 software was used in this analysis.

Kinetic analysis

To measure performance (jump height) in CMJ and kinetic variables, a force platform (Kistler Quattro Jump, AD 9290, Switzerland) with sampling frequency of 500 Hz was used. The height of vertical jumps was calculated using the flight time recorded by the platform, according to equation¹⁴:

$$h = 1/2 * (t/2)^2 * g \text{ (m)} \quad \text{Equation. 1}$$

Where, h = vertical jump height (m); t = flight time (s); g = gravity acceleration (constant 9.81m.s⁻²).

The ground reaction force data (GRF) were filtered with a low-pass but her worth filter with cut-off frequency of 10 Hz. The following variables were identified: a) vertical displacement velocity during jump, and to calculate it, acceleration curve was initially obtained by dividing the GRF values by the body mass of subjects. Subsequently, a trapezoidal integration of the acceleration curve was performed, yielding the velocity curve. The highest value obtained in this curve, which occurs immediately before the loss of foot contact with the ground (take-off) was defined as peak velocity of the gravity center (PV_{CG}); b) peak power (PP) and mean power (MP): obtained from the product between GRF and velocity, during the ascending phase of the jump; c) maximum force (F_{MAX}): highest value obtained in the ascending phase of the jump, expressed in absolute terms (N) and relativized by body mass (% BM); d) force development rate (FDR): calculated as the average slope of the force-time curve in the first 30 ms of the ascending phase.

Electromyographic analysis

Surface electromyography was used to monitor the activation of vastus lateralis (VL), rectus femoris (RF) and biceps femoris (BF) muscles, using surface electrodes (AgCL3) in bipolar configuration as recommended by SENIAM¹⁵. A reference electrode was fixed to the anterior surface of the tibia. For acquisition of EMG signal, electromyograph (Miotec, Miotool, Porto Alegre, Brazil) with four input channels operating in frequency 2000 Hz was used.

Raw signals were filtered using a combination of 5th order band-pass Butterworth filters between 20 and 500 Hz. The Root Mean Square (RMS) values of each muscle were calculated for each jump phase (ascending phase and descending phase). A trigger was used to synchronize the EMG with the video camera and thus determine the beginning and end of each phase. The RMS values were normalized to the highest RMS value obtained in the ascending phase of the three attempts of CMJ_{PREF} jump.

Statistical treatment

Data on the jump with the best performance among the three trials of each situation (PREF, <90° and >90°) were used for statistical analysis. Initially, data were submitted to descriptive statistics (mean and standard deviation) for the presentation of results. Subsequently, data normality was tested by the Shapiro-Wilk test, which showed normality of data for all variables

($p > 0.05$). In addition, the assumption of sphericity could be assumed by the result of the Mauchly test ($p > 0.05$), indicating equal variances. Then, jump height, kinetic, kinematic and electromyographic variables between CMJ_{PREF} , $CMJ > 90^\circ$ and $CMJ < 90^\circ$ conditions were compared by applying ANOVA with design for repeated measures of one factor (i.e. jump condition). *Post-hoc* Bonferroni test was used to identify the locations of differences between conditions tested. Statistical significance adopted was set at $p \leq 0.05$. Statistical analyses were performed using SPSS version 11.5.

RESULTS

Table 1 shows the comparisons of performance and kinetic parameters among the three conditions tested. Height at $CMJ > 90^\circ$ was lower ($F = 60.69$, $p < 0.001$) compared to PREF ($p < 0.001$) and $< 90^\circ$ situations ($p < 0.001$). PP showed difference ($F = 17.61$, $p < 0.001$) among all positions analyzed. Higher values at position $> 90^\circ$ were found, compared to PREF ($p = 0.046$) and $< 90^\circ$ ($p < 0.001$). PP showed difference ($F = 23.23$, $p < 0.001$) between positions, with lower values being observed at position $< 90^\circ$ compared to PREF ($p = 0.001$) and $> 90^\circ$ ($p < 0.001$). Both normalized and absolute F_{MAX} showed differences ($F = 12.60$, $p < 0.001$, $F = 11.02$, $p < 0.001$, respectively) among positions. Both for normalized and absolute F_{MAX} , the highest values were found at position $> 90^\circ$ compared to PREF ($p < 0.001$, $p = 0.001$, respectively) and $< 90^\circ$ ($p = 0.003$, $p = 0.006$, respectively). However, there was no difference between PREF positions and $< 90^\circ$. FDR did not differ among the three situations analyzed ($F = 1.89$, $p = 0.173$).

Table 1. Comparison of jump height and kinetic parameters obtained in CMJ performed at different knee flexion levels.

| | CMJ_{PREF} | $CMJ < 90^\circ$ | $CMJ > 90^\circ$ | OP |
|---------------------------------|-------------------------|------------------------|------------------------|------|
| Height (cm) | 37.83 ± 5.27^a | 38.51 ± 5.67^a | 33.25 ± 4.50^b | 1.0 |
| MP ($W \cdot kg^{-1}$) | 28.11 ± 5.08^a | 26.83 ± 4.47^b | 29.29 ± 4.91^c | 1.0 |
| PP ($W \cdot kg^{-1}$) | 52.81 ± 9.16^a | 50.74 ± 8.71^b | 53.41 ± 9.06^a | 1.0 |
| F_{MAX} (N) | 19206.68 ± 285.92^a | 1909.14 ± 310.52^a | 2106.32 ± 314.50^b | 0.96 |
| F_{MAX} ($N \cdot kg^{-1}$) | 23.25 ± 2.43^a | 23.09 ± 2.40^a | 25.51 ± 2.66^b | 0.98 |
| FDR ($N \cdot s^{-1}$) | 2590.91 ± 1563.13 | 3107.64 ± 2286.67 | 2236.45 ± 1348.37 | 0.34 |

MP = mean power; PP = peak power; F_{MAX} = maximum strength; FDR = force development rate; PO = observed power. Different letters represent differences among CMJ_{PREF} , $CMJ < 90^\circ$ and $CMJ > 90^\circ$ conditions, while same letters show no difference between situations.

Table 2 shows the comparisons of peak velocity (PV) and angular velocities of hip (AV_{QUA}), knee (AV_{JOE}) and ankle (AV_{TOR}). Difference ($F = 47.50$, $P < 0.001$) was found for PV among conditions, in which position $> 90^\circ$ showed the lowest value compared to PREF ($p < 0.001$) and $< 90^\circ$ ($p < 0.001$) than in turn, did not show any difference ($p = 0.087$). As for angular velocities, difference was observed in AV_{QUA} ($F = 8.03$, $p = 0.001$) and AV_{JOE} ($F = 7.78$, $p = 0.002$). AV_{QUA} was lower in position $> 90^\circ$ when compared to positions PREF ($p = 0.006$) and $< 90^\circ$ ($p = 0.011$), with no difference between

them ($p = 1.00$). Higher AV_{JOE} values were found in position PREF compared to $<90^\circ$ ($p = 0.05$) and $>90^\circ$ ($p = 0.007$). AV_{TOR} showed no difference between jumps performed in the three positions ($F = 2.05$, $p = 0.141$).

Table 2. Comparison of peak linear velocity and angular velocity obtained in CMJ performed at different knee flexion levels.

| | CMJ _{PREF} | CMJ $<90^\circ$ | CMJ $>90^\circ$ | OP |
|--|------------------------------|------------------------------|------------------------------|------|
| PV _{CG} (m.s ⁻¹) | 2.81 ± 0.18 ^a | 2.84 ± 0.19 ^a | 2.68 ± 0.17 ^b | 1.0 |
| AV _{QUA} (graus.s ⁻¹) | 665.10 ± 96.18 ^a | 651.97 ± 91.74 ^a | 601.10 ± 83.84 ^b | 0.89 |
| AV _{JOE} (graus.s ⁻¹) | 978.69 ± 104.19 ^a | 915.71 ± 133.90 ^b | 894.39 ± 113.09 ^b | 0.81 |
| AV _{TOR} (graus.s ⁻¹) | 1004.17 ± 107.69 | 975.56 ± 101.15 | 1005.95 ± 121.56 | 0.38 |

PV = peak velocity; VA = angular velocity; PO = observed power in the test. Different letters represent differences ($P \leq 0.05$) between CMJ_{PREF}, CMJ $<90^\circ$ and CMJ $>90^\circ$ conditions, while the same letters show no difference between situations.

Figure 2 shows the comparisons of EMG activity (% RMS) of RF (panel A), BF (panel B) and VL (panel C) muscles during the ascending phase of the CMJ. There was no difference between PREF, $<90^\circ$ and $>90^\circ$ positions for RF ($F = 0.03$, $p = 0.971$) and BF muscles ($F = 1.93$, $p = 0.162$). VL muscles showed significant difference ($F = 6.18$, $p = 0.005$) among the three positions in CMJ, with higher values in position $>90^\circ$, comparing PREF ($p = 0.018$) and $<90^\circ$ positions ($p = 0.05$).

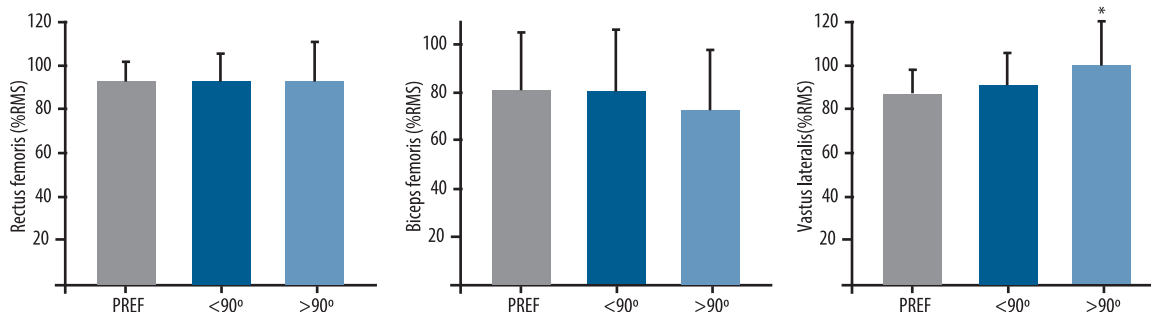


Figure 2. Comparison of EMG activation (% RMS) of rectus femoris (A), biceps femoris (B) and vastus lateralis (C) muscles during the ascending phase of the CMJ performed at different knee flexion levels. * Indicates greater EMG activation in CMJ $>90^\circ$ compared to CMJ_{PREF} and CMJ $<90^\circ$.

Figure 3 shows the comparison of EMG values of RF (panel A), BF (panel B) and VL (panel C) muscles in the descending phase in the three CMJ situations. RF ($F = 0.71$, $p = 0.482$) and BF muscles ($F = 1.64$, $p = 0.185$) showed no significant difference between the three positions analyzed. Difference was found between conditions for VL muscles ($F = 5.79$, $p = 0.008$), with higher values in position $>90^\circ$ compared with PREF ($p = 0.035$) and $<90^\circ$ ($p = 0.029$).

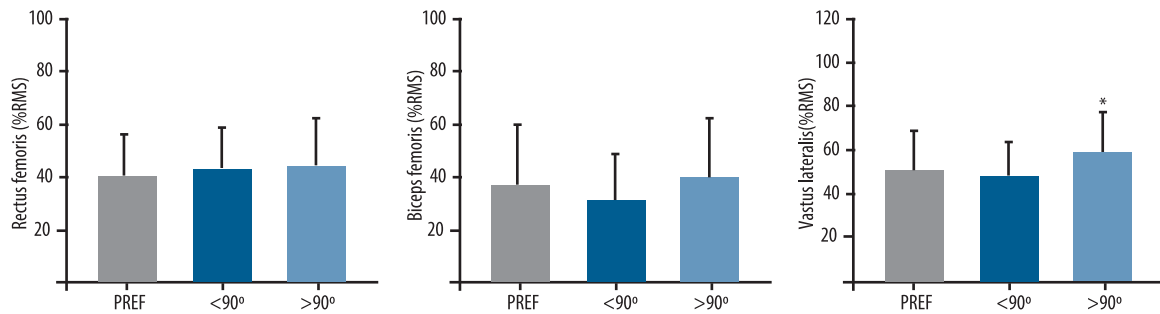


Figure 3. Comparison of EMG activation (% RMS) of rectus femoris (A), biceps femoris (B) and vastus lateralis (C) muscles obtained during the descending phase of the CMJ performed at different levels of knee flexion. * Indicates greater EMG activation in CMJ>90° compared to CMJPREF and CMJ <90°.

DISCUSSION

The main result of the present study was that the performance in CMJ changed according to squat depth or knee flexion magnitude. These changes in performance can be explained primarily in terms of changes in muscle length resulting from modulations of joint angles achieved in this study. It is known that there is an “optimum” muscle length for the production of power, so that in shortened or lengthened muscle lengths, the force produced is diminished⁴, possibly damaging motor performance.

The results showed that the heights obtained in jumps performed with maximum knee flexion preferred or less than 90° (higher squat depth) are larger than those obtained in lower squat depth (>90°). These results corroborate results of previous investigations^{7,8,13} that demonstrated a direct relationship between squat depth and CMJ performance. According to Moran and Wallace¹⁶, CMJ performance improves 17% when the jump is performed with knee flexion of 90° compared to 70° (0° represents full extension). Similar results were also observed by Salles et al.¹³, who recorded the best performance in jumps performed with greater range of motion (90° of knee flexion) compared to positions of smaller amplitude (50° of knee flexion), in which 0° indicates full extension.

Seeking to understand and find the possible causes of differences in CMJ performance, kinetic, kinematic and electromyographic analyses of movement were performed. Initially, in the case of the kinetic variables considered causative of movement, it was found that the maximum force (relative or absolute) and power showed the higher values in jumps performed in the lower squat depth (>90°), which corroborated other investigations⁷⁻⁸ in which CMJ performed in lower squat depth resulted in the highest power and strength levels.

However, it is interesting the fact that in the situation tested >90° that was found that the highest strength and power values, the best performance was not observed. This suggests that maximum strength becomes more crucial in situation in which the time for impulse transmission (“break” the inertia) is smaller, as is the case of CMJ>90°, in which higher strength and power values have been recorded. In CMJ<90°, with more time for force application and impulse transmission, less strength values were observed.

Thus, these data suggest that to achieve the best performance, longer time for applying force should be used (higher squat depth) so that the development of the maximum force has lower priority. It is noteworthy that such a strategy seems interesting in situations where the maximum strength of an individual is compromised (e.g. fatigue, injuries, low force fitness).

Regarding FDR, considered critical in vertical jump performance¹⁷, it was found that the modulation of the joint angles and their direct effects on muscle length does not appear to change it in CMJ.

As for the kinematic variables, it was found that PV_{CG} was higher in CMJ performed with higher squat depth, confirming the results of previous investigations⁸⁻¹³. Possibly, the fast speed obtained in this situation is due to the longer application of force and / or acceleration⁸. Several authors²⁻¹⁸ point out that PV_{CG} obtained when the foot leaves the ground is considered the main determinant of the vertical jump height, since, ultimately, the maximum height reached in jump is univocal function of the take-off velocity¹⁹.

According to Vanrenterghem et al.²⁰, the angular velocity of segments is one of the determining factors so that a higher translation speed of the center of mass is achieved. In this study, the highest AV_{QUA} , for example, was obtained in CMJ<90°, and PREF situations where the highest linear speeds of center of mass and better performance were observed. It has been observed that in vertical jumps performed with higher squat depth, higher knee and hip flexion angles was obtained¹⁰⁻¹⁶. This maneuver becomes inevitable in jumps with greater amplitude seeking to maintain body balance⁵. The increased angular displacement occurred in the hip eventually resulted in higher angular velocity at this position (CMJ<90°), positively influencing in a higher take off speed and therefore the jump performance.

Finally, analyzing the EMG data collected, it was found that the VL muscle showed increased activation in CMJ>90° than in other situations (PREF and <90°), both during the negative and positive phases. This result contrasts with the study by Salles et al.¹³, in which the EMG activity of this muscle was greater in jumps performed at 90° and lower at 50° of knee flexion (0° = full extension). Bobbert et al.⁹ observed no changes in EMG activation of the vastus lateralis muscle while performing vertical jumps at five different knee flexions. In the present study, the lowest EMG activation observed in VL during CMJ performed in higher squat depth may be due to the increased participation of elastic elements (in parallel) in force production in this type of jump. According to Herzog et al.¹¹ in dynamic actions, in addition to contractile elements, the total muscle strength production is greatly influenced by the elastic elements. Thus, if in greater muscle lengths, greater contribution of these elements was observed, the involvement of the contraction “machinery” (sarcomere) would be reduced, decreasing neuronal recruitment and hence the EMG activity¹¹⁻²¹.

For biarticular RF and BF muscles, the RMS values were similar during the concentric phase in the three situations tested. Likewise, Mohamed et al.²¹ also observed no differences in EMG activity when the length of the biarticular muscles was changed by manipulating the extension/flexion

degree of knee and hip. The fact that there are no changes in EMG of these muscles as a function of knee flexion may be related to its biarticular nature. According to Escamilla²², it is difficult to determine whether the hamstring and RF muscles (except short head biceps), for being biarticular, act eccentric or concentric during jump. According to the author, they may even act isometrically during movement. During the ascending phase of CMJ, for example, RF muscles shorten with knee extension and extend with hip extension. As a result, these muscles may not produce a substantial change in its length and thus not modify the EMG activity pattern in jumps performed with different knee flexion angles.

CONCLUSIONS

We concluded that height and biomechanical variables at CMJ are influenced by squat depth defined by the level of knee flexion angle. It was found that the greatest heights were obtained in jumps performed from higher squat depth, a situation that also recorded the highest vertical velocity at the take-off moment and the highest angular velocities. Moreover, lower force production and less EMG activation of the vastus lateralis muscle were observed in these situations. So, flexing more the knees (under 90) could be a technical strategy to be used by athletes in order to optimize the vertical jump performance with countermovement in training and competitions.

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