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original article

Kinetic parameters as determinants of vertical jump performance

Parâmetros cinéticos determinantes do desempenho nos saltos verticais

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Abstract – This study evaluated force and velocity parameters of vertical jump performance in countermovement jump (CMJ) and squat jump (SJ) and compared results for sprint runners and volleyball players. Twenty-four male athletes (12 regional/national--level sprint runners and 12 national-level volleyball players) performed CMJ and SJ on a force platform. The following variables were analyzed: jump performance (jump height and power), peak velocity (PV), absolute and relative maximum force (MF), rate of force development (RFD,) and time to reach maximum force (TMF). In CMJ, jump height was correlated with PV (r=0.97) and normalized MF (r=0.47), whereas jump power was significantly correlated with all variables, except MF (r=0.12). In SJ, PV and normalized MF were significantly correlated with jump height (r=0.95 and r=0.51) and power (r=0.80 and r=0.87). In addition, TMF was inversely correlated with power (r=-0.49). Runners had higher performance variables (height and power), normalized MF and PV than volleyball players in both CMJ and SJ. Velocity and maximum force were the main determinants of height and power in the two types of vertical jumps. However, explosive force (RFD and TMF) was also important for power production in vertical jumps. Runners had a better vertical jump performance than volleyball players.

Key words: Force; Performance; Power.

Resumo – *Este estudo objetivou identificar parâmetros de força e velocidade relacionados com o desempenho nos saltos verticais (SV) Counter Movement Jump (CMJ) e Squat Jump (SJ); comparar estes parâmetros entre corredores velocistas e voleibolistas. Participaram 24 atletas do sexo masculino (12 velocistas de nível estadual/nacional e 12 voleibolistas de nível nacional). Os atletas realizaram os SV CMJ e SJ sobre uma plataforma de força, sendo analisadas variáveis de desempenho (altura do salto e potência), pico de velocidade (PV), força máxima (Fmax) absoluta e relativa, taxa de desenvolvimento de força (TDF) e tempo para atingir a força máxima (TFmax). No CMJ, a altura correlacionou-se com o PV (r=0,97) e com a Fmax normalizada (r=0,47), enquanto que a potência relacionou-se com todas as variáveis, exceto com a Fmax absoluta (r=0,12). No SJ, o PV e a Fmax normalizada correlacionaram-se com a altura obtida (r=0,95; r=0,51, respectivamente) e com a potência (r=0,80; r=0,87, respectivamente). Além disso, a TFmax também correlacionou-se com a potência (r=-0,49). Os velocistas apresentaram valores superiores nas variáveis de desempenho do salto (altura e potência), na Fmax e no PV, tanto no SJ como CMJ. Conclui-se que o pico de velocidade e a força máxima normalizada foram os principais determinantes da altura e da potência obtida em ambos os SV. Contudo, a força explosiva (TDF e TFmax) também mostrou-se importante na produção de potência nos SV. Por fim, os velocistas apresentaram melhor desempenho nos SV em relação às voleibolistas.*

Palavras-chave: *Força; Potência; Performance.*

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INTRODUCTION

Vertical jump (VJ) performance is one of the best indications of lower limbs muscle power[1] . VJ is an important predictor of performance in several sports that require explosive action, such as sprint running and volleybal[2-5].

Biomechanically, power is characterized as the rate of work per time unit, specifically calculated as force multiplied by speed. According to evidence described by Hill[6], there is a hyperbolic relation between these variables, and an optimal combination of force and speed should be achieved to optimize the production of power. This combination of loads will vary according to the characteristics of the player and the type of training, in which the stronger and/or slower individuals usually achieve their maximum power at lower speeds than the faster ones.

Several characteristics of force, such as maximum force (MF), time to reach maximum force (TMF) and the rate of force development (RFD), are associated with VJ performance[8-10]. RFD, defined as the rate of force increase in a given time interval, is an important parameter to measure neuromuscular performance of athletes in sports that use explosive muscle contractions[8,11]. Movements in certain sports modalities, or, more specifically, technical components, do not use all their force potential for movements; in such cases, this rate of force variation, known as explosive force, is more important[11].

The force parameters that determine lower limbs muscle power are associated with VJ performance, particularly in countermovement jump (CMJ) and squat jump (SJ)[5,10]. In the first, there is an eccentric movement of agonist muscles followed by a concentric movement, and jump performance results, mostly, from the use of the elastic energy produced in the stretch-shortening cycle (SSC). In SJ, however, there is only the concentric work phase, and the performance is assigned basically to the neural recruitment capacity of the athlete[1]. As a result of such CMJ and SJ characteristics, in which force and velocity parameters are required in different ways, there is a difference of about 2-4 cm in jump height[12].

The force and velocity parameters that determine power may have different characteristics according to the action performed in each sports: sprinters need power to move in the shortest time possible, and volleyball players need the power to jump. The identification of these aspects may be useful when defining the specific characteristics of training for sports that require explosive action, but different movements. This study aimed: (i) identified the force and velocity parameters associated with CMJ and SJ performance; and (ii) compared these parameters for sprint runners and volleyball players.

METHODS

Subjects

Twenty-four male athletes participated in this study: 12 were sprint runners (age: 21.2 ± 3.3 years; body mass: 69.0 ± 5.6 kg; height: 175.5

± 6.5 cm; fat: 8.3 ± 1.8%) and 12 were volleyball players (age: 23.6 ± 4.1 years; body mass: 85.5 ± 16.2 kg; height: 196.7 ± 12.8 cm; fat: 9.9 ± 2.8%). Sprint runners were athletes in the state of Santa Catarina, Brazil, and participated in regional and national competitions; and the volleyball players were members of a professional team that plays in the Brazilian Volleyball Super League.

Participants received explanations about the purposes and methods of the study before signing an informed consent term. The study was approved by the Ethics Committee on Research with Human Beings of Universidade Federal de Santa Catarina (073/2007).

Instruments and Procedures

Before data collection, the athletes stretched and warmed up for a short time and then received technical instructions and trained specifically for VJ to ensure that the protocol was standardized. This stage included about 5 to 6 CMJ and SJ at intervals of about 1 min, and the number of jumps depended on the movement technique that each individual presented. After that, the athletes performed three CMJ and, after a 2 min recovery interval, the SJ. The vertical jumps were performed on a piezoelectric force platform (Kistler®, Quattro Jump, 9290AD, Winterthur, Switzerland), which measured the vertical component of ground reaction force (GRF) at a frequency of 500 Hz.

CMJ and SJ

To perform CMJ, the athlete started at a static standing position with hands on the hip, and the jump was preceded by a countermovement of acceleration below the center of gravity achieved by flexing their knees to about 90 degrees, an angle that was observed and visually controlled by the examiner. During the jump, the trunk was kept as vertical as possible, and the athlete was instructed to jump at the highest possible speed and to the highest point that they could reach. In this protocol, the agonist muscles were stretched during descent, when the elastic structures were stretched, and there was an accumulation of elastic energy that could be used when going up (concentric phase). In SJ, the athlete started the jump from a static position, with the knees at an angle of about 90 degrees, the trunk as vertical as possible, and the hands on the waist. The jump was performed without any countermovement, and there was only the concentric action of the agonist muscles involved in the movement.

Data analysis

GRF values measured by the platform were acquired using the *Quattro Jump* software (Kistler). Figure 1 shows GRF, acceleration, velocity and position during CMJ. The same curves were defined for SJ and may also be seen in Figure 1. However, the beginning of the SJ was set at time point c because there was no eccentric phase preceding the concentric phase.

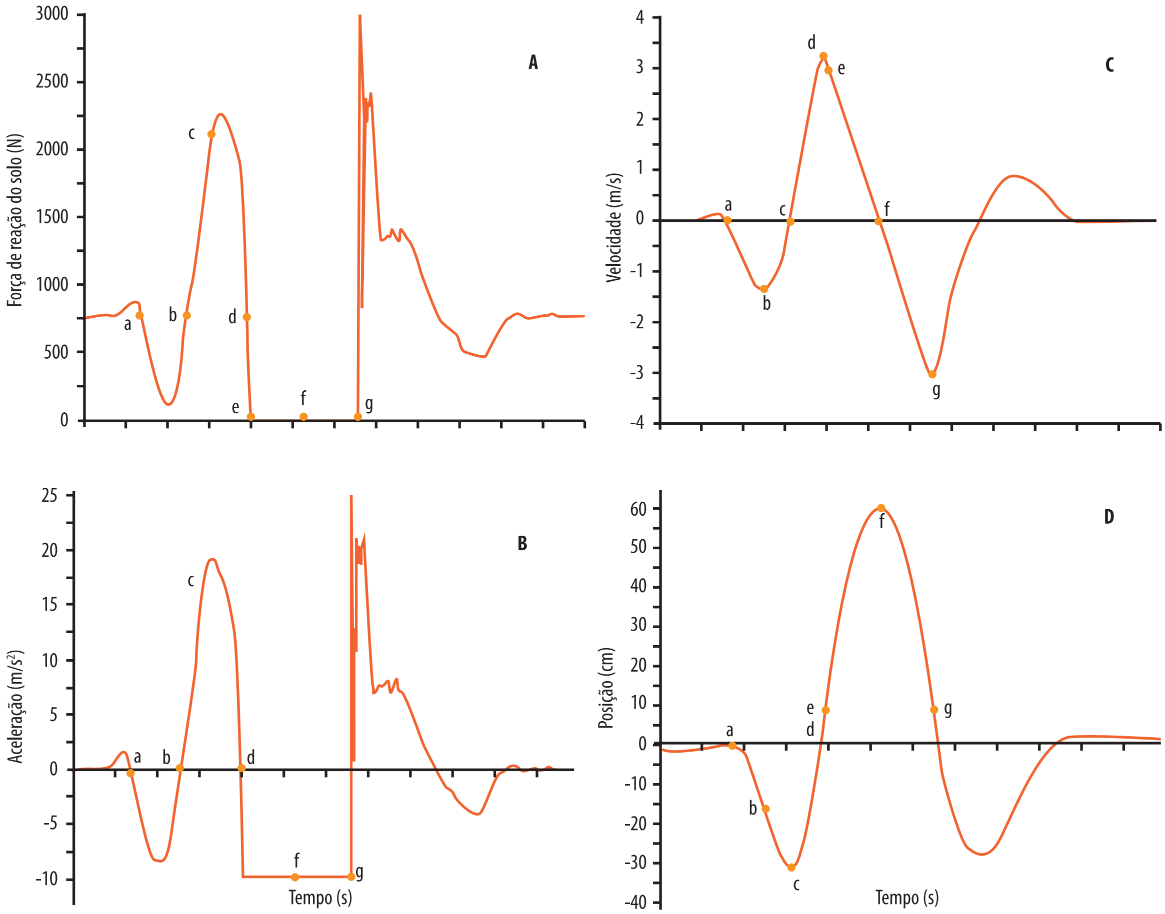

Figure 1. Kinetic parameters of CMJ. (a) beginning of jump; (b) point at which GRF is equal to body weight propulsion and acceleration is zero, which indicates point at which jumper begins to accelerate up; (c) beginning of concentric phase, characterized by movement in which velocity becomes positive; (d) GRF is equal to body weight propulsion and jumper reaches maximum velocity upwards; (e) propulsion, when GRF is equal to zero; (f) jumper is at maximum jump height, and velocity is zero; (g) landing (adapted from Linthorne)[13].

Based on the data collected, the following variables were measured and evaluated:

a) jump height: calculated using the *Quattro Jump* software and the method of double force integration. First, the acceleration curve was calculated (Figure 1-B) by dividing GRF values by body mass, measured in the platform itself. After that, a trapezoidal integration of the acceleration curve was used to obtain the velocity curve (Figure 1-C). The latter was integrated again to obtain distance at each time point of the movement, and the greatest vertical distance (Figure 1-D, time point f) was entered as the jump height.
b) power: calculated by multiplying GRF by velocity at the concentric phase of the jump (c-e); the mean value of the curve was used for analysis. The beginning of the concentric phase was identified both in CMJ and SJ as the time when velocity became positive (Figure 1-C, time point c).

c) maximum force (MF): identified as the highest value obtained in the concentric phase of the jump expressed in absolute values (N) and normalized according to body mass raised to 0.67th power ($m^{0.67}$)[14].
d) time to reach maximum force (TMF), measured in the concentric phase (c-e).
e) rate of force development (RFD): the mean slope of the force-time curve in the time interval of 0-30 ms corresponding to the beginning of the concentric phase (c).
f) peak velocity (PV): The highest value in C curve (time point d), which occurred immediately before the foot lost contact with the ground (e).

Statistical analysis

Descriptive statistics and the Shapiro-Wilk test were used to check data normality, and results showed that all variables had a normal distribution. The Levene test confirmed that the groups had a homogeneous variance for all variables under analysis and that parametric statistics could be used. After that, the Student *t* test for independent samples was used to compare results for sprint runners and volleyball players, and the Pearson correlation, to evaluate the association between VJ variables. The level of significance was set at $p < 0.05$.

RESULTS

Table 1 shows the associations of vertical jump performance parameters (height and power) with the force and velocity variables obtained for SJ and CMJ.

Table 1. Correlation of jump height and power with force and velocity variables in SJ and CMJ

	CMJ		SJ	
	Height	Power	Height	Power
RFD	0.13	0.44 *	-0.04	0.34
MF	0.05	0.12	0.06	0.02
Normalized MF	0.47 *	0.88 **	0.52 **	0.76 **
TMF	-0.07	-0.46 *	-0.07	-0.49 *
PV	0.97 **	0.75 **	0.95 **	0.80 **

RFD: rate of force development; MF: maximum force; TMF: time to reach maximum force; PV: peak velocity.
* p<0.05; ** p<0.01

As shown in Table 1, CMJ height was strongly correlated with PV, whereas mean CMJ power was associated with all variables, except absolute MF. In SJ, PV and normalized MF determined the height achieved, and the same variables, together with TFmax, were associated with SJ power.

Table 2 compares the results of VJ variables for sprint runners and volleyball players.

According to the results in Table 2, both CMJ and SJ performances (jump height and power) were better among sprint runners than volleyball players. Of the parameters that explain force and velocity, relative MF and PV were also greater for sprint runners in both vertical jumps.

Table 2. Descriptive values (mean ± SD) of parameters measured in CMJ and SJ performed by sprint runners (SRUN) and volleyball players (VOL)

	CMJ		SJ	
	SRUN	VOL	SRUN	VOL
Height (cm)	54.72 ± 5.46 *	48.38 ± 3.96	51.93 ± 4.81 †	45.30 ± 4.07
Power ($W.kg^{-1}$)	33.31 ± 4.99 *	27.95 ± 2.93	27.63 ± 3.28 †	22.59 ± 2.88
MF (N)	1842.49 ± 211.24	2045.15 ± 320.54	1806.48 ± 255.12	2032.23 ± 326.53
MF ($N.kg^{-0.67}$))	24.67 ± 2.47 *	22.50 ± 2.33	25.49 ± 2.28 †	22.28 ± 1.71
TMF (ms)	75 ± 40	79 ± 41	170 ± 70	202 ± 70
RFD ($N.s^{-1}$)	2863.81 ± 2021.14	2880.56 ± 1212.01	5447.61 ± 2009.74	5311.11 ± 1669.79
PV ($m.s^{-1}$)	3.04 ± 0.15 *	2.85 ± 0.13	2.93 ± 0.13 †	2.74 ± 0.14

RFD: rate of force development; MF: maximum force; TMF: time to reach maximum force; PV: peak velocity.
* significant difference of CMJ variables between sprint runners and volleyball players ($p<0.05$)
† significant difference of SJ variables between sprint runners and volleyball players ($p<0.05$)

DISCUSSION

CMJ and SJ height, classified as the main performance determinant, was associated with PV and normalized Fmax. Previous studies with other sports had already shown that MF is a determinant of SJ and CMJ height[5,9,10,15], and PV, of CMJ height[16]. PV was a determinant of CMJ height also in our study, probably because there was a countermovement or downward acceleration of the CG (eccentric phase) before the propulsion phase (concentric), and, therefore, the contact with the ground occurred at a high velocity. An important mechanism in this type of eccentric-concentric movement is the stretch-shortening cycle. In this cycle, the elastic structures of the agonist muscles are stretched during descent in CMJ, and there is an accumulation of elastic energy that may be used when going up (concentric phase)[17] which contributes to the VJ performance. According to Ugrinowitsch et al.[15], the amplitude of the countermovement used by the athlete is determinant for the efficiency of the stretch-shortening cycle and, consequently, for CMJ height.

In addition to elastic energy, other countermovement mechanisms may contribute to making PV and MF the major determinants of the height achieved in CMJ. According to Bobbert and Casiuus[12], muscle stretching in the eccentric phase activates neural responses and increases muscle stimulation in the concentric phase. This enables the muscles to build an active pre-contraction state, in which a large number of crossed bridges is formed and establishes an adequate length-tension relation to generate propulsion. Moreover, a rapid transition from the concentric to the eccentric phases[18] and tendon stiffness[19] may contribute to generating velocity and, consequently, to CMJ performance.

The height achieved in SJ was also associated with PV. This jump has no countermovement or eccentric phase, and the only muscle action is during the concentric phase of movement[1]. In this sense, the velocity generated and, consequently, the height achieved are basically assigned to the athlete's capacity of neural recruitment[20], without the contribution of the mechanisms described above, which are found only in movements with an eccentric phase. However, normalized MF was also correlated with SJ height, which indicates that the performance in this jump was determined by both velocity and maximum force. The fact that MF was a determinant in this type of movement may be explained by the fact that the individual starts the jump from a static and semi squatting position, and more force should be used to accelerate the body. This corroborates the results of previous studies that found an association between maximum and dynamic isometric force and SJ performance[8,5,10], which shows that athletes with a higher level of maximum force have better SJ performances.

The power obtained in VJ, another performance marker, is determined by the rate of work performed and the time that it takes to perform the movement ($P=W.t^{-1}$). If work is equal to the force multiplied by distance, and distance divided by time is velocity, then power may be expressed as force multiplied by velocity (P=F.V); that is, the force that a body segment may produce according to the velocity of the segment[7]. In our study, this was confirmed by the significant correlations of normalized force and velocity with CMJ and SJ power.

The level of power produced depends on the association of force and velocity, as demonstrated in the studies conducted by Hill,[6] who found a hyperbolic association of the velocity of contraction and the tension produced when analyzing the mechanical behavior of the muscle. Based on this theory, the greater the load to move, the greater the force to be produced by the contractile components of the muscle and the lower the velocity of shortening of these structures and of the segment to be moved. According to Bosco[21], the primary explanation for such phenomenon seems to be the loss of tension at the moment when the actin-myosin bridges break inside the contractile component, which are restored under resting conditions. The second explanation is the viscosity found in both the contractile component and the connective tissue.

VJ power does not depend only on MF, but also on other characteristics associated with force, such as RFD and TMF, according to the results of our study. In this sense, time to reach maximum force and the rate of force development are important elements in the production of power[5,22]. RFD, one of the indices most often used to represent explosive force, is calculated according to the mean slope of the force-time curve[11]. This index was significantly correlated only with CMJ power, in which there was a greater slope of the force-time curve than of the SJ curve. According to Corvino et al.[11], this association is more evident in countermovement conditions, in which the SSC occurs and enables greater velocity and force variation in a shorter time. In contrast, TMF, also used as an index of explosive force, was correlated with both CMJ and SJ, which suggests that athletes that reach maximum force earlier have a greater VJ power, regardless of the eccentric phase.

Although they perform different movements, both sprint runners and volleyball players need high levels of power to enable the first to move in the shortest time possible to the end of a race and the latter to perform vertical movements that are important for attack hits and blocks. The second objective of this study was to compare the performance and the force and velocity parameters obtained in SJ and CMJ performed by sprint runners and volleyball players. Performance (jump height and power) in both jumps was superior in the group of sprint runners. Of the variables that explain the performance observed, normalized maximum force and peak velocity were greater in the group of sprint runners, both in CMJ and SJ.

These results partly confirm those reported by Kollias et al.[23], who found that sprint runners reached greater maximum force and velocity in VJ than volleyball, football and basketball players. However, differently from our study, Kollias et al.[23] also found that sprint runners had higher explosive force parameters (rate of force development and time to reach maximum force) than players of other sports. In addition, Ugrinowitsch et al.[15] found that sprint runners had a better CMJ performance than players of other sports because sprint runners generated greater propulsion and acceleration in the concentric phase of the jump.

Such force and velocity parameters, determinant of VJ performance, are dependent on factors of structural, mechanic and functional nature[19,24]. One of these factors, that may partly explain the differences between these athletes, is their genetic load and, more specifically, the composition of muscle fibers, as demonstrated in a study[24] that analyzed SJ performance in groups of individuals with > 60% and < 40% fast fibers, measured by means of histological examination of the vastus lateralis. They found that SJ height in the first group (36.7 cm) was greater than in the second (33.8 cm); in addition, the group with the greater percentage of fast fibers was able to apply more force in a shorter space of time, which enabled them to generate higher power levels. The effect of fiber composition in VJ performance was also confirmed by the results of studies[25,26] that found that individuals with a higher proportion of fast fibers generated greater levels of force in a short time in the eccentric phase of movements, as in CMJ.

The characteristics of training in these sports may also explain the differences found[23]. The type of exercise used by sprint runners for neuromuscular purposes is performed both in the form of short sprints and multi-jumps (usually plyometrics), and both are considered efficient to increase the levels of power[27]. As volleyball players are basically trained using multi-jumps for muscle power[28], sprints may be determinant in the generation of greater force and velocity and, consequently, better VJ performance[29]. Kollias et al.[23] also found that specific training with short sprints (10-30 m) resulted in greater force and potency of sprint runners in vertical jumps than of athletes that practiced the other sports under analysis. Moreover, the combination of plyometrics and force training seems to be more effective for VJ performance that isolated plyometric training[15]. Based on these findings, it may be recommended that physical trainers of volleyball players should adopt sprint sessions in combination with multi-jumps and plyometrics to improve VJ performance.

One of the main limitations of this study was the lack of control of the genetic load of athletes, more specifically of the type of muscle fiber, which directly affects VJ performance[30]. In addition, the use of other biomechanical methods, such as kinesiology and electromyography, might have provided complementary information.

CONCLUSION

Peak velocity and normalized maximum force were the main determinants of height and power in both types of VJ. However, the results of this study also suggest that RFD and TMF are important in the production of power, which indicates that the athletes with greater explosive force may be the ones with the higher levels of VJ power. Finally, sprint runners had a better VJ performance than volleyball players, probably due to the effect of their characteristic training.

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