Coordination and power during Squat Jumps with loads controlled by an electromechanical dynamometer

Gustavo Bermúdez[1], Elia Mercado-Palomino[2], Andrés González[1], Luis Javier Chirosa[3], Adriana Valentina Silva-Pereyra[1,4], Gabriel Fábrica[5]

[1]*Instituto Universitario Asociación Cristiana de Jóvenes, Montevideo.*
[2]*Human Motion Analysis Laboratory, Instituto Mixto Salud y Deporte, Granada.*
[3]*Departamento de Educación Física y Deportiva, Facultad de Ciencias del Deporte, Universidad de Granada.*
[4]*Instituto Superior de Educación Física, Universidad de la República, Montevideo.*
[5]*Departamento de Biofísica, Facultad de Medicina, Universidad de la República, Montevideo.*

Abstract*— The coordination between lower limb segments and power output developed during Squat Jumps in different load conditions was analyzed in ten trained male subjects (age 22.5±2.1 years; body height 176.5 ±5.4 cm; body mass 75.8 ±5.8; BMI 24.3± 1.8). We used a functional electromechanical dynamometer to control added load, 0% to 30% of body weight during the push-off phase. Significant differences between load conditions were evaluated by one-way repeated-measures ANOVA, p <0.05, for jump height, maximum vertical force, maximum vertical speed, and maximum angular speeds of the hip, knee and ankle. Pearson correlation coefficients were calculated to examine the relationships between jump height and the other variables. Angular velocities that presented significant differences between conditions were considered to analyze coordination through the graphs of the angular speed average values per condition during push-off phase. Power output decreased with the load and showed higher correlation with jump height at 30% load. This indicates that power training with SJ must be carried out without load, but to evaluate the power through the SJ height, a load of at least 30% should be used. Maximum articular velocities of hip and knee changed with increasing load and were correlated with height at 30% load. The final values and slope at the beginning of the push-off phase of relationship between hip and knee speed, indicate different coordination for 0% and load conditions and suggest a greater transfer from rotational to vertical speed in jumps without added load.
***Keywords*— Vertical jump, human coordination, performance evaluation.**

Resumen*— Se analizó la coordinación entre los segmentos de las extremidades inferiores y la potencia durante Squat Jumps en diferentes condiciones de carga en diez sujetos varones entrenados (edad 22.5 ± 2.1 años; altura corporal 176.5 ± 5.4 cm; masa corporal 75.8 ± 5.8; IMC 24.3 ± 1.8). Utilizamos un dinamómetro electromecánico funcional para controlar la carga del 0% al 30% del peso corporal durante la fase de empuje. Las diferencias entre las condiciones se evaluaron mediante ANOVA de medidas repetidas de una vía, p <0.05, para altura de salto, fuerza vertical máxima, velocidad vertical máxima y velocidades angulares máximas de cadera, rodilla y tobillo. Se calcularon los coeficientes de correlación de Pearson para examinar las relaciones entre altura del salto y las otras variables. Las velocidades angulares que presentaron diferencias se consideraron para analizar la coordinación mediante los gráficos de promedios durante la fase de empuje. La potencia disminuyó con la carga y tuvo mayor correlación con la altura en 30%. Esto indica que el entrenamiento de potencia con SJ debe realizarse sin carga, pero para evaluar potencia con la altura se debe utilizar una carga de al menos 30%. Las velocidades articulares máximas de cadera y rodilla cambiaron con la carga y se correlacionaron con la altura en 30%. Los valores finales y la pendiente inicial de la relación entre velocidad de cadera y rodilla, indican una coordinación diferente con y sin carga y sugieren una mayor transferencia de velocidades rotacionales a vertical en saltos sin carga adicional.
***Palabras clave*— Saltos verticales, coordinación en humanos, evaluación de rendimiento.**

I. INTRODUCTION

The development of high-power values through the action of the neuromuscular system is considered a primary objective to improve performance in various sports practices [1, 2, 3]. This capacity is usually estimated indirectly by the height reached in vertical jumps [4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. However, the relevance of power as a variable associated with jump height has been discussed. The latter depends on the mechanical impulse [14, 15] given that the linear velocity of the center of mass (CoM) in take-off is the variable of primary importance. Furthermore, the only way to generate such linear velocity is giving the body segments an angular velocity [16, 17]. In addition, the performance of a squat jump (SJ) is strictly bound to some qualities of the muscular-skeletal system that the jumper must optimally exploit to reach a maximum flight height [18]. Jump height is thus influenced by the coordination of the jumper's segments during the push-off phase [16, 17]. The coordination pattern in SJ can be assessed by image analysis of the angular actions of the hip, knee and ankle in the sagittal plane [6, 7, 17]. When humans perform maximum height SJ, their segmental rotations contribute in a proximodistal sequence to the vertical velocity of CoM [17]. This sequence prevents a take-off position in which the muscles have not been able to produce work over their full shortening range, ensures a balanced contribution of segmental angular velocities to the vertical velocity of CoM, and helps maximize the efficacy of the work produced [17]. Other movement patterns have been reported in SJ during push-off when strength capacity and muscle coordination are altered [19]. A situation of interest in sports in which these alterations can occur is in jumps with added load [20, 21].

The studies of vertical jumps with added load allow to evaluate changes in the force-velocity and power-velocity curves and, therefore, contribute to a better understanding of the relationships between the action of the neuromuscular system and the mechanical properties and functional performance on sports [22, 23, 24, 25, 26]. External load inevitably affects the kinematic pattern and the overall efficiency of the muscular system [1, 23]. For example, the evidence suggests that the addition of loads of about 30% of body weight causes drastic changes in the jump pattern [10]. One of the most important limitations in loaded vertical jump studies is strict load control. The most interesting option that has been used to achieve it is to add a load that mimics the weight added on the CoM, but not the inertia [9, 20]. Since this was done using tensioned elastic bands, the authors indicate that they were only able to keep the load approximately constant during the thrust and that the effect is maintained when the subject is in the air. By using a new multi-joint Isokinetic Dynamometer [27], which allows controlling the loads in different free movements [28, 29], it is possible to add a constant load only during the push-off phase.

There is an increasing use of loaded vertical jumps in training and insufficient discussion regarding the effect of coordination on jump height, which is considered a reflection of power. In this work, we present an analysis of the mechanical power output and segmental coordination during push-off in SJ with different loads controlled by a dynamic dynamometer. Based on previous studies, we hypothesized that the power output decreases with the load and it is not a fundamental variable for the resulting height. Meanwhile, there are changes in the coordination pattern assessed through angular actions of lower limbs in the sagittal plane that can explain height changes in loaded SJ.

II. Methods

A. Subjects

The sample size for this work was estimated based on data reported in previous studies [10, 30], and on Cohen´s guidelines [31], with an alpha level of 0.05 and power level of 0.8. Ten trained male subjects (age 22.5±2.1 years; body height 176.5 ±5.4 cm; body mass 75.8 ±5.8; BMI 24.3± 1.8) were selected on the basis of their sport experience as athletes in handball and soccer. All the subjects had at least two years of previous strength and power training, more than five years of sports experience and a training frequency of at least three times a week and athletic proficiency. None of the subjects had any illnesses or injuries that would affect the test results. Before testing, all subjects were informed of the study procedures and were required to sign an informed consent. The study was conducted following the requirements stipulated in the Declaration of Helsinki. The protocol and informed consent received approval from the corresponding University Ethics Committee (approval number 772).

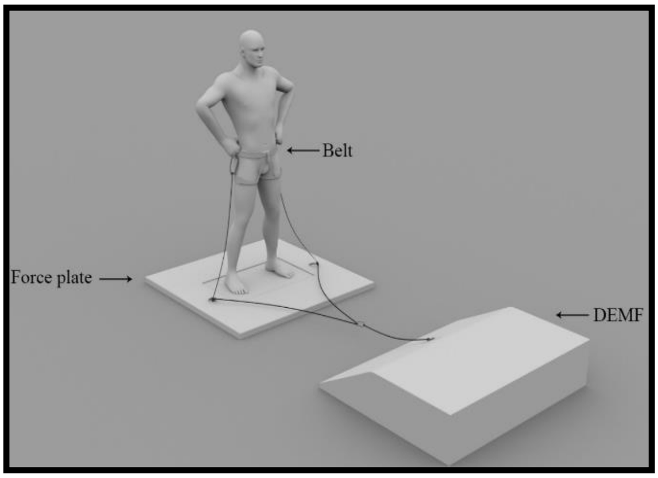

Fig. 1: Schematic representation of the pulley system used to produce constant positive vertical load with DEMF during the performance of SJ.

B. Study design

To address our study purpose, we recorded vertical force during push-off in SJ on a piezo-electric triaxial force plate with dimensions of 50cm x 60cm (Kistler Instruments, Hampshire, UK; sampling frequency 200 Hz). The movement during the push-off phase was reconstructed from the records of 45 markers [32], obtained with a three-dimensional photogrammetric system (Qualisys Inc., Gothenburg, Sweden), based on 8 high-speed infrared cameras (250 fps) with high resolution (3 MP). The study was carried out in four load conditions: 0%, 10%, 20% and 30% of the body weight of each participant. This control was carried out using a functional electromechanical dynamometer (DEMF) (Dynasystem® Model DynaBlackbox) in tonic mode [28, 29]. The dynamometer pulled on each side of a climbing harness belt placed at the subject’s waist through a low-friction pulley system similar to previous studies (Fig. 1).

Changes in the load were controlled directly using the force plate through the record of the vertical component of force before the start of each jump. To determine the load order, we proposed a design of counterbalanced measures, trying to keep the number of subjects within the experimentally manageable. Therefore, the 0% load condition was fixed at the beginning or end of each jump sequence. The rest time between each jump within each condition was 2 minutes, and a 5-minute break was taken between each load condition. During the capture, fatigue was controlled with the Borg scale.

C. Procedures

Prior to the commencement of testing, participants performed a 15-minute standardized warm-up. Subsequently, the subjects performed five jumps in each load condition (0%, 10%, 20% and 30% of body weight). Before each jump, the participants were weighed for approximately four seconds in an upright standing position with the added load. Then, they stood with a knee flexion angle of approximately 90°. After maintaining the initial position of the SJ [4] for 3 seconds, which was controlled with a manual goniometer, they were instructed to jump as high as possible without performing any countermovement. The hands remained at the waist throughout the movement.

Vertical force component values and trajectories of the markers were exported to MATLAB R2017a ® (Mathworks, Inc.) to perform the determination of variables. Jump height (h), vertical force maximum values (Fm), center of mass speed (Vm) and power output (Pm) were determined from force records. From the 3D reconstruction values, the maximum angular velocities in the sagittal plane of the hip (VmH), knee (VmK) and ankle (VmA) were determined. Angular velocities that presented significant differences when comparing loads were considered to analyze the coordination in different load conditions. For this part of the study, we considered that two premises must occur for a good SJ: a distal proximal sequence with the lower limb joints, and a balanced contribution of segmental angular velocities to the vertical velocity of CoM to maximize the efficacy of the muscular work produced [17]. Based on this, a descriptive analysis of the variation of the hip and knee speed was performed. The values during the push-off phase were normalized in time and discretized with 50 points for each jump analyzed. Then, the values of each point were averaged by condition.

D. Statistical analyses.

To assess reliability, we calculated the coefficient of variation (CV%) with the five measurements of h, Fm and Vm obtained for each subject and intraclass correlation coefficients (ICC) for each load situation. Once reliability was confirmed we only considered the highest jump for subsequent analyzes. Data are presented as mean and standard deviations (SD). Data distribution was checked using the Shapiro–Wilk's normality test. The significant differences between load conditions were tested by one-way repeated-measures ANOVA, the alpha level was set at $p<0.05$ for all analyses. Pearson correlation coefficients were calculated to examine the relationships between h and the other variables considered. All statistical analyses were conducted using the software SPSS (22.0, IBM Corporation, NY, USA).

TABLE II
CORRELATION OF THE VARIABLES WITH THE JUMP EIGHT.

III. Results

The CV% and ICC for all the variables considered in this study were always less than 0.1 and 0.8, respectively. The results of the Shapiro-Wilk's normality test allowed to assume normality for all the variables. Table I shows the maximum values of the variables considered in each load condition. Table II presents the results of correlations of the each variable in each condition with jump height. In both tables the asterisks indicate significant differences. Figure 2 shows the relationships between hip and knee speed changes during the push-off phase for each condition.

	0%	**10%**	**20%**	**30%**
h (m)*	0.27 (0.05)	0.25 (0.04)	0.20 (0.04)	0.18 (0.05)
Pm (W)*	1558.6 (248.7)	1477.9 (238.3)	1243.4 (257.5)	1136.1 (334.7)
Fm (N)*	891.3 (121.9)	880.2 (95.2)	847.4 (144.6)	784.5 (147.9)
Vm (m.s^{1})*	2.3 (0.2)	2.3 (0.2)	2.1 (0.2)	2.1 (0.3)
VmH (°.s^{-1}) *	521.8 (35.6)	480.2 (45.45)	459.6 (49.5)	460.9 (39.7)
VmK (°.s^{1})*	587.1 (54.2)	564.8 (62.8)	554.7 (55.13)	548.5 (54.5)
VmA (°.s^{1})	315.9 (141.5)	358.3 (139.6)	349.3 (144.3)	347.4 (143.6)

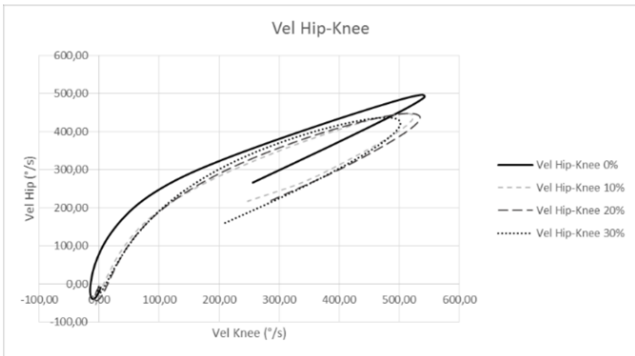

Fig. 2: Average values of the relationship between hip and knee speed during the push-off phase for each condition. Each relationship was obtained by averaging point by point the data obtained from the normalized curves of the ten subjects analyzed.

TABLE I
MAXIMUM VALUES OF THE VARIABLES ANALYZED AND RESULTS OF COMPARISON BETWEEN THE DIFFERENT LOAD CONDITIONS.

	0%	**10%**	**20%**	**30%**
Pm (W)	0.76*	0.84*	0.78*	0.90*
Fm (N)*	0.26	0.06	0.37	0.65*
Vm (m.s1)*	0.99*	0.99*	0.99*	0.99*
VmH (º.s-1) *	0.17	0.26	0.28	0.72*
VmK(º.s1)*	0.12	0.18	0.24	0.80*
VmA (º.s1)	0.02	0.11	0.11	0.23

IV. Discussion

The present study was designed to analyze jointly the coordination pattern of lower limbs and power output developed during the push-off phase in SJ with different dynamometer to perform strict control of added load in a range of 0% to 30% of body weight. The load control strategy used allows us to affirm that load was constant throughout the push-off phase of the jump. This is a fundamental difference with previous works done. The relationships analyzed in this study could provide a simplified approach of analyzing both the design and function of the human muscular system [9].

As expected, the jump height decreased significantly as the load increased. This decrease was accompanied by a decrease in force and a decrease in maximum speed since the height in the jump directly depends on the take-off speed [13, 17]. It is necessary to clarify that this work did not consider the absolute force but the effective force, this is, the useful force on the CoM movement. Although force and speed do not peak simultaneously during the push-off phase, they are the parameters commonly used for power evaluation in jumps [33]. The maximum power output does not coincide in time with either of the two peaks (force or speed) but corresponds to the moment when their product is maximized, and decreases with the load. However, the power output shows a higher correlation with the jump height only with 30% load. This, we believe, is of interest to coaches and athletes because it suggests that power training should be done without load. On the other hand, if power is evaluated through height, there is a greater correspondence when jump is made with a high percentage of added load. The relationship between power output and height in vertical jumps has been previously discussed [14, 15], and performance is considered to depend on the mechanical impulse, that is, on the speed that the subject can develop rather than power. In accordance with the latter, a high correlation of speed and height was observed in all load conditions. According to our results, it only makes sense to consider the height as a reflection of the power output when the SJ is performed with a 30% added load. The explanation for this is that the force developed becomes important in addition to speed.

In relation to the coordination of the jumper's segments during push-off phase, the results of the hip and knee angular velocity peaks showed significant decreases with load. No statistically significant differences were observed for ankle action based on this parameter. Previous works have discussed the importance of the action of a light segment distal to head-arms-trunk set [17]. We could say that the contribution of foot movement at the end of kinematic chain does not change with load or that load does not significantly affect the action of muscles responsible for this action. However, the correlation results indicate that values of maximum articular velocities in sagittal plane are not important when considered in isolation for jump performance, except with a 30% load. For a joint analysis of the kinematic chain coordination, we considered only angular values of the hip and knee, since these presented

significant differences when comparing loads. A first visual analysis of the curves of angular values of hip and knee during push-off phase, normalized in time and discretized, suggests a difference in joint action with and without load.

The more pronounced increase in the curve in 0% load condition at the beginning of the push-off phase, indicates a predominance of hip action over knee action in that situation. This is consistent with previously found results where it is established that, in a good jump, the push-off is initiated by activation of the hip extensor muscles [34]. The maximum point reached can also be a descriptive parameter of the coordination of interest obtained with this type of curves. In this case, the highest value achieved is consistent with the maximum angular velocity values reached in a 0% load condition. The most important and novel finding of this investigation is given by what the final values of the hip and knee speed curves suggest. That point indicates what happens with these two joints during take-off. This result is important because in vertical jumps the shortening range of muscles depends on the take-off position [17, 15]. According to theoretical approximations, the proximodistal sequence in muscle activation patterns and segmental rotations allows the system to achieve a take-off position in which the joints are as extended as possible, so that the monoarticular hip extensors, knee extensors, and plantar flexors produce as much work as possible [6, 7, 17]. However, there is a geometric problem inherent to the transformation from segment rotation to CoM translation. In theory, the transfer of angular to vertical speed is maximum when a segment is horizontal, but zero when the segment is vertical, that is when the maximum extension is reached. The take-off at higher hip and knee speeds with 0% load can be interpreted as an intermediate situation in which there is a greater transfer of rotational to vertical speeds (a greater component of vertical speed), which favors the height reached.

V. Conclusions

The power output is not a height determining variable in all load conditions. If high power values are sought, training must be carried out without load. Nevertheless, to evaluate the power through the SJ height, an additional load of at least 30% of body weight should be used.

Height differences in SJ could be explained by the coordination of the joint action of the kinematic chain of lower limbs. The final values and initial slope of the relationship between hip and knee speed during push-off suggests different coordination with and without load that determine a greater or minor transfer of rotational to vertical speeds.

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