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Original Article

Kinetic variables and vertical stiffness of female volleyball players during a vertical jump

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Abstract:
Problem statement.Vertical jump is an essential motor skill in many sports, especially in volleyball where the total number of jumps performed by a player during training and games is high. Lower-extremity stiffness seems to greatly affect the storage and utilization of elastic energy during stretch-shortening cycles and the rate of force development; higher levels of lower-extremity stiffness seem to be necessary for higher vertical jump height. ***Approach.*** A total of eight female volleyball players (16.00 ± 1.07 years, 166.00 ± 4.04 cm, 57.02 ± 8.73 kg) and eight female sedentary participants (15.13 ± 1.36 years, 161.13 ± 6.71 cm, 50.70 ± 5.42 kg) volunteered to participate in this study. They performed countermovement jumps with and without arm swing; kinetic variables and vertical stiffness were analyzed. ***Purpose.*** The aim of this investigation was to analyze kinetic variables and vertical stiffness of adolescent female volleyball players during a vertical jump. ***Results.*** Significant differences between volleyball players and sedentary participants were observed in flight height, maximum vertical displacement of the center of mass, acceleration impulse, average power, peak power, and vertical stiffness ($p < 0.01$). No significant differences were observed in average force or peak force. Female volleyball players had significantly higher values of almost all kinetic variables analyzed compared to sedentary subjects of the same age range. However, because they had greater vertical displacement of the center of mass without differences in the peak force, they showed a significantly lower vertical stiffness values. ***Conclusions.*** A specific training to increase vertical stiffness can make volleyball players more impulsive subjects and lead to better use of elastic energy during the stretch-shortening cycle, which will increase vertical jump height.
Keywords: Countermovement; Biomechanics; Sports performance; Leg stiffness; Stretch-shortening cycle

Introduction

Vertical jump is an essential motor skill in many sports (Reiser et al., 2006; Sarvestan et al., 2018). The success of many volleyball actions (e.g., serves, spikes, and blocks) strongly depends on the ability of a player to jump high and fast (Hale et al., 2019; Sánchez et al., 2018; Vaverka et al., 2016; Ziv and Lidor, 2010).

The number of jumps varies according to the player's position but, in any case, the total number of jumps performed by a player during trainings and games is high (Ziv and Lidor, 2010), and players try to maintain maximum performance from the beginning to the end of a game (Freitas-Junior et al., 2020). Lian et al. (1996) stated that volleyball game includes approximately 60 maximal jumps per hour of game play.Tillman et al. (2004)determined that female teams of NCAA Division I performed an average of 45 jumping acts by each player in the two games analyzed, and Reeserand Bahr (2017) reported that volleyball players may perform between 30,000 and 40,000 jumping movements in a single year.

Maximal vertical jump is frequently used for assessing muscular strength and power of lower limbs (Sáez de Villarreal et al., 2009; Sarvestan et al., 2018), and extensive research has been conducted to determine kinematic/kinetic parameters that must be improved to increase vertical jump height (Linthorne, 2001; Policastro et al., 2020). Lower-extremity stiffness is one of the parameters that has gained popularity in the last decade owing to its association with athletic performance and lower-extremity injuries (Goodwin et al., 2019; Serpell et al., 2012; Waxman et al., 2018). Stiffness describes the resistance of a given structure to change in its length once force is applied to it (Brughelli and Cronin, 2008; Kuitunen et al., 2011; McMahon and Cheng, 1990).It seems that lower-extremity stiffness greatly affects the storage and utilization of elastic energy during stretch-shortening cycles and the rate of force development (Brughelli and Cronin, 2008; Kalkhoven and Watsford, 2018); increases in stiffness may lead to an increase in explosive power and vertical jump height (Wu et al., 2010).

The concept of stiffness is based on Hooke's law for an ideal spring (Butler et al., 2003; Serpell et al., 2012).During running and jumping, legs can be modeled as a spring with the body mass sitting at the top (Butler et al., 2003; Goodwin et al., 2019; Serpell et al., 2012). During the stance phase, the musculoskeletal system

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stores elastic energy, which can be restituted during the subsequent push-off phase (Kuitunen et al., 2011; Laffaye et al., 2005; McMahon and Cheng, 1990).

When the movement occurs in the vertical direction (e.g., jumps), lower-extremity stiffness is called vertical stiffness (Butler et al., 2003), and there are several methods to calculate it (Brughelli and Cronin, 2008; Serpell et al., 2012). The most commonly used method is described by McMahon and Cheng (1990); thus, lower-extremity stiffness is equal to the peak vertical ground reaction force (VGRF) divided by the maximal vertical displacement of the center of mass. Although it is usually calculated during hopping or running, recently, some studies have also used it during a vertical jump (Boullosa et al., 2018; Jordan et al., 2018; Sheppard, 2016).

Higher levels of lower-extremity stiffness seem to be necessary for optimal stretch-shortening cycle utilization and higher vertical jump height (Korff et al., 2009). However, too much stiffness may increase lower-extremity injury risk by reducing the capacity to attenuate VGRF during the landing phase of a jump (Maloney et al., 2016; Waxman et al., 2018). These contradictory results suggest that there may be an optimal stiffness range to enhance performance and reduce lower-extremity injury risk(Butler et al., 2003; Waxman et al., 2018).

Volleyball is a sport that is characterized by the high number of jumps performed by players, and kinetic variables and vertical stiffness during the contact phase of jumps are expected to have high values. These parameters have been recently studied in young female subjects of other high intensity intermittent disciplines (Rojano, 2021; Rojano-Ortega, 2021) but not in young female volleyball players. Therefore, the aim of this study was to analyze kinetic variables and vertical stiffness of 14–18-year-old recreational female volleyball players during a vertical jump. Our hypothesis was that the values of both kinetic variables and vertical stiffness would be higher in volleyball players than in sedentary subjects of the same age range.

Materials and methods

Participants

A total of 16 adolescent female Andalusian subjects (14–18 years old) volunteered to participate in this study; eight of them were volleyball players from teams participating in Andalusian competitions (16.00 ± 1.07 years, 166.00 ± 4.04 cm, 57.02 ± 8.73 kg); the players trained at least 4.5 hyper week. The other eight subjects were sedentary (15.13 ± 1.36 years, 161.13 ± 6.71 cm, 50.70 ± 5.42 kg).None of the participants had experienced serious injuries at least three months before the testing sessions. All parents or legal tutors provided written informed consent according to the Declaration of Helsinki.The study was approved by the University Research Ethics Committee.

Procedures

The jumps used to evaluate kinematic variables and vertical stiffness were the countermovement jump (CMJ) with and without arm swing. These jumps are similar to those in many sports and are performed with the contribution of the stretch-shortening cycle. CMJs without arm swing are performed with the hands placed on the hips. CMJ shave eccentric (downward movement) and concentric (upward movement)phases. To take advantage of energy stored by the elastic elements of the muscles, there has to be a minimum stop between eccentric and concentric phases (Bosco, 1999; González and Rivas, 2002).CMJ with an appropriate use of arm swings can increase jump height by at least 15% (Harman et al., 1990; Vaverka et al., 2016).

A preparatory session was performed several days before data collection. During the second session, after a 15-min warm-up routine, all participants performed 5 submaximal CMJs without arm swing and 5 submaximal CMJs with arm swing. After 5-min rest, they performed 3 final jumps of each type with a minute rest between them. These final jumps were used for data collection, and participants were allowed to jump with their preferred self-selected countermovement depth and were instructed to perform all jumps with maximal effort.

Data collection and analysis

All data were collected using a Kistler Quattro Jump force platform at a sample rate of 500 Hz. Force platforms at a sample rate of 500 Hz have previously shown high reliability for peak force (ICC = 0.92), peak velocity (ICC = 0.98), and peak power (ICC = 0.98) during CMJ(Hori et al., 2009).

Quattro Jump Software, v.1.1.1.4 was used to obtain force–time, velocity–time, displacement–time, and power–time curves. Force–time curves were obtained directly by the platform. VGRF minus jumper's weight was the resultant force on the jumper's center of mass. Velocity–time curves were obtained by numerically integrating acceleration (resultant force divided by jumper's body mass) with respect to time using the trapezoid rule. Displacement–time curves were obtained by numerically integrating velocity with respect to time using the trapezoid rule. Finally, power values were calculated as the product of force and velocity.

The end of eccentric phase and the initiation of concentric phase were defined as the time point when the center of mass velocity transitioned from negative to positive. The following variables of the highest CMJ of every subject with and without arm swing were analyzed:

- *Flight height:*difference between the subject's center of mass position at take-off and the subject's center of mass position at the highest part of the flight

- *Maximal vertical displacement of the body's center of mass:* difference between the subject's center of mass position at the beginning of countermovement and the subject's center of mass position at the end of the eccentric phase
- *Average force*: average value of VGRF during the concentric phase of the jump
- *Peak force:*maximum value of VGRF during the eccentric phase of the jump
- *Concentric impulse:*mechanical impulse calculated during the concentric phase of the jump
- *Concentric impulse duration*
- *Average power:*average value of power during the concentric phase of the jump
- *Peak power:*maximum value of power during the concentric phase of the jump
- *Absolute vertical stiffness:*peak VGRF divided by the maximal vertical displacement of the center of mass (McMahon and Cheng, 1990)
- *Normalized vertical stiffness*:absolute vertical stiffness divided by the subject's body mass

Statistical analysis

Statistical analysis was performed using the program SPSS for Windows, v. 22.0 (SPSS Inc., USA). The means and standard deviations of all variables were calculated. Shapiro–Wilk test was applied to test data normality. When this condition was fulfilled, Student's t-tests were performed to determine significant differences between groups. When normality condition was not fulfilled, Mann–Whitney U tests were performed. Results were considered to be statistically significant if $p < .05$.To determine the magnitude of the difference between groups, measures of effect size were assessed using Cohen's d: minimal effect (<0.20), small effect (0.20–0.50), moderate effect (0.50–0.80), or large effect (>0.80) (Cohen, 1988).

Results

Means and standard deviations of all variables obtained by each group in CMJ without arm swing are shown in Table 1. Significant differences between groups and effect sizes are also shown in Table 1.

Table 1. Descriptive statistic and differences between groups for the study variables in CMJ without arm swing

Variables	VOLLEY (N = 8)	SEDENTARY (N = 8)	SIGNIFICANT DIFFERENCES AND EFFECT SIZE	
	Mean ± Std. Dev.	Mean ± Std. Dev.	Significance	Cohen's d
Flight height (cm)	24.58 ± 2.48	16.81 ± 2.29	**	3.26
Maximal DCOM (cm)	27.48 ± 4.63	17.20 ± 4.31	**	2.30
Average Force (BW)	1.87 ± 0.08	1.87 ± 0.21	--	0.00
Peak Force (BW)	2.30 ± 0.26	2.16 ± 0.30	--	0.50
CI (BW · s)	0.259 ± 0.010	0.215 ± 0.018	**	3.02
CI duration (s)	0.240 ± 0.027	0.200 ± 0.040	*	1.17
Average power ($W \cdot kg^{-1}$)	24.10 ± 2.21	20.46 ± 2.65	*	1.49
Peak Power ($W \cdot kg^{-1}$)	42.76 ± 3.64	36.19 ± 4.52	*	1.60
Absolute K_{vert} ($kN \cdot m^{-1}$)	4.84 ± 1.36	6.98 ± 2.23	--	−1.16
Normalized K_{vert} ($kN \cdot m^{-1} \cdot kg^{-1}$)	0.085 ± 0.019	0.125 ± 0.042	--	−1.23

*Std. Dev.: Standard Deviation; DCOM: displacement of the center of mass; BW: body weight; CI: concentric impulse; K_{vert}: vertical stiffness. *:p < .05; **: p < .01*

Significant differences between groups were observed in the flight height, maximal displacement of center of mass,and concentric impulse ($p < .01$), as well as in the concentric impulse duration, average power, and peak power ($p < .05$).

Means and standard deviations of all variables obtained by each group in CMJ with arm swing are shown in Table 2. Significant differences between groups and effect sizes are also shown in Table 2.

Table 2. Descriptive statistic and differences between groups for the study variables in CMJ with arm swing

Variables	VOLLEY (N = 8)	SEDENTARY (N = 8)	SIGNIFICANT DIFFERENCES AND EFFECT SIZE	
	Mean ± Std. Dev.	Mean ± Std. Dev.	Significance	Cohen's d
Flight height (cm)	29.59 ± 4.49	20.55 ± 3.06	**	2.35
Maximal DCOM (cm)	27.61 ± 8.99	20.52 ± 4.84	--	0.98
Average Force (BW)	1.88 ± 0.20	1.82 ± 0.15	--	0.34
Peak Force (BW)	2.17 ± 0.47	2.16 ± 0.23	--	0.03
CI (BW · s)	0.280 ± 0.013	0.233 ± 0.022	**	2.60
CI duration (s)	0.278 ± 0.056	0.234 ± 0.043	--	0.88
Average power ($W \cdot kg^{-1}$)	25.06 ± 4.02	21.29 ± 2.49	*	1.13
Peak Power ($W \cdot kg^{-1}$)	48.97 ± 2.43	39.07 ± 5.28	**	2.41
Absolute K_{vert} ($kN \cdot m^{-1}$)	4.76 ± 1.92	5.47 ± 1.54	--	−0.41
Normalized K_{vert} ($kN \cdot m^{-1} \cdot kg^{-1}$)	0.086 ± 0.039	0.108 ± 0.030	--	−0.63

*Std. Dev.: Standard Deviation; DCOM: displacement of the center of mass; BW: body weight; CI: concentric impulse; K_{vert}: vertical stiffness. *:p < .05; **: p < .01*

Significant differences between groups were observed in the flight height, concentric impulse, and peak power ($p < .01$) as well as in the average power ($p < .05$).

Significant differences that were observed for both types of CMJ were similar but not exactly the same. In addition, even when vertical stiffness and normalized vertical stiffness values were very different, with moderate and large effect sizes, no significant differences between groups were observed probably owing to the small number of subjects in each group. Thus, we decided to analyze variables of CMJ with and without arm swing pooled together. Means and standard deviations of all variables obtained by each group for CMJ with and without arm swing are shown in Table 3. Significant differences between groups and effect sizes are also shown in Table 3.

Table 3. Descriptive statistic and differences between groups for the study variables for CMJ with and without arm swing

Variables	VOLLEY (N = 8)	SEDENTARY (N = 8)	SIGNIFICANT DIFFERENCES AND EFFECT SIZE	
	Mean ± Std. Dev.	Mean ± Std. Dev.	Significance	Cohen's d
Flight height (cm)	27.04 ± 4.35	18.68 ± 3.25	**	2.18
Maximal DCOM (cm)	27.54 ± 6.90	18.86 ± 4.58	**	1.48
Average Force (BW)	1.87 ± 0.15	1.85 ± 0.17	--	0.12
Peak Force (BW)	2.23 ± 0.37	2.16 ± 0.26	--	0.22
AI (BW · s)	0.269 ± 0.016	0.224 ± 0.022	**	2.34
Length of AI (s)	0.258 ± 0.046	0.217 ± 0.044	*	0.91
Average power ($W \cdot kg^{-1}$)	24.58 ± 3.17	20.87 ± 2.52	**	1.30
Peak Power ($W \cdot kg^{-1}$)	45.86 ± 4.38	37.63 ± 4.98	**	1.75
Absolute K_{vert} ($kN \cdot m^{-1}$)	4.80 ± 1.61	6.23 ± 2.01	*	−0.79
Normalized K_{vert} ($kN \cdot m^{-1} \cdot kg^{-1}$)	0.085 ± 0.030	0.116 ± 0.036	**	−0.94

*Std. Dev.: Standard Deviation; DCOM: displacement of the center of mass; BW: body weight; CI: concentric impulse; K_{vert}: vertical stiffness. *:p < .05; **: p < .01*

Significant differences between groups were observed in the flight height, maximal displacement of center of mass, concentric impulse, average power, peak power, and normalized vertical stiffness ($p < .01$) as well as in the concentric impulse duration and absolute vertical stiffness ($p < .05$).

Discussion

This discussion will be performed based on the analysis of data for CJM with and without arm swing pooled together.

The aim of this study was to analyze kinetic variables and vertical stiffness of14–18-year-old recreational female volleyball players during a vertical jump. The average values of flight height were significantly higher in volleyball players (27.04 ± 4.35 cm) than in sedentary subjects (18.68 ± 3.25 cm). This result was expected owing to the hours of training of volleyball players and to the high number of jumps performed by them during training and games.

The maximal displacement of center of mass was significantly higher in volleyball players (27.54 ± 6.90 cm) than in sedentary subjects (18.86 ± 4.58 cm), which confirmed the results of Sánchez-Sixto et al. (2018), who stated that deep countermovements increased net vertical impulse, which led to higher jump height.

Contrary to our initial hypothesis, we did not observe significant differences between groups in average force or peak force; in addition, effect sizes were minimal. These results are unexpected because it is logical that athletes may develop higher force that sedentary subjects. However, the relationship between applied force and vertical jump performance has shown contradictory results in scientific literature (Sánchez-Sixto et al., 2018). Kirby et al. (2011) determined that peak force negatively correlated with jump height, which suggested that peak force was possibly not the best measure for assessing vertical jump performance.

According to Linthorne (2001), concentric impulse is the main factor that affects take-off velocity and, therefore, jump height; this notion has been supported by González and Marques (2010), who showed a significant positive correlation between concentric impulse and vertical jump height, and by Kirby et al. (2011), who observed a highly significant correlation between net vertical impulse and vertical jump height in CMJ ($r = 0.925$, $p < .0001$). Therefore, our values for concentric impulse were significantly higher in volleyball players (0.269 ± 0,016 BW · s) than in sedentary subjects (0.224 ± 0.022 BW · s),and the same results were observed for concentric impulse duration (0.258 ± 0.046 s vs.0.217 ± 0.044 s). These results indicated that even if force values during the push-off phase were similar in both groups, because the maximal vertical displacement of the center of mass was higher for volleyball players, they were able to develop the same amount of force over longer distance, which resulted in a greater acceleration impulse and, consequently, in a higher vertical jump.

Average power was significantly higher in volleyball players (24.58 ± 3.17 W· kg^{-1}) than in sedentary subjects (20.87 ± 2.52 W· kg^{-1}); similar results were observed for peak power (45.86 ± 4.38 W· kg^{-1}vs 37.63 ± 4.98 W· kg^{-1}), which indicates that volleyball players need to be explosive to be more effective. These results agree with those of Harman et al. (1990)who determined that peak power correlated much better with vertical jump height ($r = 0.88$, $p < .05$) than peak force ($r = 0.49$, $p < .05$). Similar results were obtained by González and Marques (2010), who observed strong correlations between flight height and peak power ($r = 0.812$–0.851, $p < .001$) and between flight height and average power ($r = 0.57$–0.65, $p < .01$) during CMJ. Furthermore, many studies have developed different regression equations to estimate peak power based on vertical jump height alone or vertical jump height and body mass (Amonette et al., 2012).

Vertical stiffness values were significantly lower in volleyball players (4.80 ± 1.61 kN · m^{-1}) than in sedentary subjects (6.23 ± 2.01 kN · m^{-1}), and the same results were obtained for normalized vertical stiffness (0.137 ± 0.040 kN · m^{-1} · kg^{-1} vs. 0.099 ± 0.017 kN · m^{-1} · kg^{-1}). These results, although not expected, are logical because vertical stiffness is the quotient between peak VGRF and maximal vertical displacement of the center of mass (McMahon and Cheng, 1990). Thus, because there are no differences in peak force values but the maximal displacement of the center of mass is greater for volleyball players, they also have lower vertical stiffness values.

These results appear to contradict previous studies, which state that higher levels of lower-extremity stiffness are predictive of higher maximum vertical jump height (Goodwin et al., 2019; Maloney et al., 2016; Serpell et al., 2012; Waxman et al., 2018). In addition, vertical stiffness values obtained using vertical hoping tasks for soccer players and basketball players (Waxman et al., 2018) or for netballers (Pickering et al., 2017) are much higher than ours, which may indicate that an increase in volleyball players vertical stiffness may also increase their maximum vertical jump height.

Conclusions

Adolescent female volleyball players from the teams of Andalusian competitions have significantly higher values for almost all kinetic variables analyzed than sedentary subjects of the same age range.These players do not exert higher average force or peak force during the push-off phase but, because they have a greater vertical displacement of the center of mass, they develop the same amount of force over longer distance, which leads to a greater acceleration impulse and higher vertical jump. The greater displacement of the center of mass without differences in the peak force is also the reason why they exhibit lower vertical stiffness values than sedentary subjects and other types of athletes. These results suggest that a specific training to increase vertical stiffness may make volleyball players more impulsive subjects and lead to a better use of the stretch-shortening cycle, which may increase their vertical jump height.

Disclosure statement

The authors declare no conflict of interest.

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