

Comparison of kinetics and vertical stiffness of recreational female figure skaters, volleyball players, and ballet dancers during a vertical jump

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Abstract:

Problem statement. Lower-extremity stiffness is the leg's resistance to a change in its length caused by an external force. Higher values of lower-extremity stiffness have been associated with higher maximum vertical jump height. Figure skating, volleyball, and ballet are three high-intensity intermittent disciplines characterised by a large number of explosive jumps. **Approach.** Eight female figure skaters (15.38 ± 1.69 years; 159.69 ± 3.18 cm; 51.96 ± 2.69 kg), eight female volleyball players (15.63 ± 1.18 years, 165.38 ± 4.27 cm, 55.24 ± 6.95 kg), and eight female ballet dancers (15.00 ± 1.07 years, 163.25 ± 4.33 cm, 52.11 ± 4.19 kg) volunteered to participate in this study. They each performed a countermovement jump, and kinetic variables and vertical stiffness were measured using a Kistler Quattro Jump force platform at 500 Hz. **Purpose.** This study aimed to assess the differences in the kinetic variables and vertical stiffness during a vertical jump in recreational female roller figure skaters, volleyball players, and ballet dancers aged 14–18 years. **Results.** Significant differences between figure skaters and volleyball players were only found for concentric impulse duration ($p < 0.05$). However, differences in the maximum displacement of the centre of mass, average force, concentric impulse duration, absolute vertical stiffness and normalised vertical stiffness ($p < 0.05$ or $p < 0.01$) were evident between figure skaters and ballet dancers and between volleyball players and ballet dancers, and the effect sizes were large. **Conclusions.** The kinematic and kinetic mechanisms contributing to countermovement jump performance were similar for figure skaters and volleyball players. However, female ballet dancers were highly impulsive and made better use of the stretch–shortening cycle, which allowed them to perform quicker jumps.

Keywords: Lower-extremity stiffness; countermovement jump; performance; stretch–shortening cycle.

Introduction

The vertical jump is a basic motor skill in many sports (Sarvestan et al., 2018). In high-intensity intermittent sports requiring maximal jumps, the capacity of an athlete to jump high and fast can be decisive for the success of many sport actions (Hale et al., 2019; Vaverka, et al., 2016).

Figure skating is a sport that combines both artistic and athletic skills (Mazurkiewicz et al., 2018). The elements performed in roller figure skating programs are similar to those performed on ice (Dias et al., 2014), and the most difficult elements, except for dance modality, are typically the jumps. Elite male skaters frequently perform complete triple and quadruple revolution jumps (King, 2005), and in the last years, some of the highest-level female skaters have also included some quadruple revolution jumps in their programs. Thus, both male and females skaters must train their physical capabilities, such as strength, flexibility, and power, to be able to develop explosive strength with the lower extremity muscles (King, 2005).

Jumps are also an important feature in many dance styles, and a ballet dancer may perform more than 200 jumps in a typical class (Ward et al., 2019). Strength is vital for the slow and controlled movements of the performances, but power is also essential because ballet dancers must be able to execute explosive and high jumps in order to perform difficult and aesthetic elements in the air (Brown et al., 2007; Tsanaka et al., 2017). Although ballet is an artistic discipline, it requires a good physical fitness of the dancers. Along with the technical demands, they must train and consolidate physical qualities such as flexibility, muscular strength, and muscular power (Brown et al., 2007; Kenne and Unnithan, 2008).

Most of the actions performed in a volleyball match are also jump-based and require high lower-extremity explosive power (Mroczek et al., 2019). The success of these actions relies heavily on the ability of the player to jump high and fast (Hale et al., 2019; Vaverka et al., 2016). According to many authors, the number of jumps performed by a volleyball player during trainings and games is high. Tillman et al. (2004) calculated an average of 45 jumping actions per player in two games involving female NCAA Division I teams, and Reeser and Bahr (2017) reported that volleyball players may perform between 30,000 and 40,000 jumps per year.

Currently, maximal vertical jump height is used as an indicator of muscular strength and power of the lower limbs, and the strength and power of the lower limbs have been associated with sport performance (Brown et al., 2007; Sarvestan et al., 2018). Extensive research has been carried out to analyse which parameters must be improved to increase vertical jump height (Linthorne, 2001). One of these parameters is lower-extremity stiffness, which is frequently associated with athletic performance and lower-extremity injury risk (Goodwin et al., 2019; Serpell et al., 2012; Waxman et al., 2018). Stiffness can be defined as a body part's resistance to a change in its length caused by a force applied to it (Brughelli and Cronin, 2008; McMahon and Cheng, 1990). Leg stiffness appears to have an important influence on the storage and utilization of elastic energy during stretch-shortening cycle and the rate of force development (Brughelli and Cronin, 2008; Kalkhoven and Watsford, 2018).

The concept of stiffness has its origin in Hooke's Law for an ideal spring (Butler et al., 2003; Serpell et al., 2012). During running or jumping the lower extremity can be modelled as an ideal spring supporting the mass of the body (Butler et al., 2003; Goodwin et al., 2019; Serpell et al., 2012). In the eccentric part of the stance phase, the muscles, tendons, and ligaments store elastic energy, and in the concentric part of the stance phase, they release it in the form of kinetic or potential gravitational energy (Kalkhoven and Watsford, 2018).

When the movement occurs in the vertical direction, lower-extremity stiffness is called vertical stiffness (Butler et al., 2003). Vertical stiffness is most commonly determined using McMahon and Cheng's method (Brughelli and Cronin, 2008; Serpell et al., 2012), in which it is calculated as the quotient of the peak vertical ground reaction force (VGRF) and the maximum centre of mass displacement (McMahon & Cheng, 1990). Although this method has traditionally been used during hopping or running, recent investigations have also used it to analyse leg stiffness during vertical jumps (Jordan et al., 2018; Sheppard, 2016).

Higher values of lower-extremity stiffness have been associated with higher maximum vertical jump height (Korff et al., 2009) and improved sprinting performance and running economy (Butler et al., 2003), but too much stiffness has also been linked to greater lower-extremity injury occurrence (Butler et al., 2003; Watsford et al., 2010; Waxman et al., 2018). Therefore, it seems that there may be an optimal range for stiffness that enhances athletic performance and minimises injury risk (Waxman et al., 2018).

Figure skating, volleyball, and ballet are three high-intensity intermittent disciplines characterised by a high number of explosive jumps performed during trainings and the competitions or ballet performances, and the kinetic variables and vertical stiffness values in the contact phase of the jumps are predicted to be high. However, to our knowledge, no studies have compared the differences in these variables between these three groups. Therefore, the purpose of this study was to analyse the differences in the kinetic variables and vertical stiffness during vertical jumps in recreational female roller figure skaters, volleyball players, and ballet dancers aged 14–18 years. It was hypothesised that the kinematic and kinetic mechanisms and vertical stiffness contributing to vertical jump performance would be different between groups.

Material and methods

Participants

Twenty-four adolescent female Andalusian athletes aged 14–18 years volunteered to participate in this study. Eight of them were female figure skaters (15.38 ± 1.69 years; 159.69 ± 3.18 cm; 51.96 ± 2.69 kg), eight were female volleyball players (15.63 ± 1.18 years, 165.38 ± 4.27 cm, 55.24 ± 6.95 kg) and the other eight were female ballet dancers (15.00 ± 1.07 years, 163.25 ± 4.33 cm, 52.11 ± 4.19 kg). The groups were considered similar in terms of age, body height and body mass because no significant differences were found between them regarding these three variables. All of them had a minimum experience of 4 years and performed regular training for more than 4.5 hours per week. To ensure that participants were at the same level, they were selected from those who could finish on the podium in regional competitions but not in national competitions.

None of the subjects had experienced serious injuries at least three months before the testing sessions. All participants over 18 years of age and the parents or legal tutors of all participants under 18 years of age gave written informed consent according to the Declaration of Helsinki. The study was approved by the University Research Ethics Committee.

Procedures

The countermovement jump (CMJ) was used to evaluate kinematic variables and vertical stiffness. The CMJ can be carried out with or without an arm swing and is performed with the contribution of the stretch-shortening cycle. It has an eccentric phase (downward movement) and a concentric phase (upward movement). To take advantage of the energy stored by the elastic elements of the muscles, the stop between the eccentric and concentric phases must be minimised (Bosco, 1999). Our previous not published work with ballet dancers showed that the use of arms increased their jump height less than 6%. However, Harman et al. (1990) reported that the arm swing increased more than 20% the jump height of eighteen physically active male subjects and Vaverka et al. (2016) reported an increase of more than 35% the jump height of eighteen elite male volleyball players. Therefore, ballet dancers do not make a good use of the arm swing, probably due to the restricted arm motion of the aesthetic movements performed in the choreographies. Thus, for the purpose of this study, we only investigated CMJs without arm swings.

One familiarization session was carried out some days before the data collection. In the experimental session participants performed a general 10 minutes warm-up routine, which included low-intensity aerobic exercise, stretching exercises and two sets of five submaximal jumps. After 5 minutes rest they performed 5 maximal jumps with a minute rest between them. Participants were allowed to jump with their preferred self-selected countermovement depth and they were instructed to jump “as high as possible”. All sessions were performed at the same time of the day (between 17:00 and 19:00 hours).

Data collection and analysis

All data were collected using a Kistler Quattro Jump force platform at a sample rate of 500 Hz. The reliability of force platforms with a sample rate of 500 Hz has previously been shown for peak force (ICC = 0.92), for peak velocity (ICC = 0.98) and for peak power (ICC = 0.98) during a 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 the jumper’s weight was the resultant force on the jumper’s centre of mass. Velocity–time curves were obtained by numerically integrating acceleration (resultant force divided by the 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, also using the trapezoid rule. Finally, power values were calculated as the product of force and velocity. The end of the eccentric phase and the initiation of the concentric phase was defined as the time point at which the center of mass velocity transitioned from negative to positive. The mean values of the variables obtained from the three highest jumps were used for subsequent analysis and the following variables were analysed:

- Jump height: difference between the subject’s centre of mass position at take-off and the subject’s centre of mass position at the highest part of the flight.
- Maximum vertical displacement of the body’s centre of mass: difference between the subject’s centre of mass position at the beginning of the countermovement and the subject’s centre 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: mechanic impulse 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 with SPSS program for Windows, v. 22.0 (SPSS Inc., USA). The means and standard deviations of all the variables were calculated. Data were tested for normality using the Shapiro-Wilk test and, as this condition was not fulfilled, Kruskal-Wallis H test was used to determine if there were significant differences between the three independent groups. Post-hoc Mann-Whitney U tests with Bonferroni correction were performed to determine significant differences between each two groups. Results were considered statistically significant if $p < 0.05$. In addition, 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). Variables with p values ranging between 0.05–0.09 and an effect size greater than 0.50 were defined as providing a clinically meaningful difference (Millet et al., 2016).

Results

The means and standard deviations of all the variables obtained for each group are shown in Table 1. Significant differences between groups and effect sizes are also shown in Table 1.

Table 1. Descriptive statistics and differences between groups for the study variables.

Variables	Skaters (N = 8)	Volley (N = 8)	Ballet (N = 8)	Skaters– Volley	Skaters– Ballet	Volley– Ballet
	Mean ± sd	Mean ± sd	Mean ± sd	Cohen’s d	Cohen’s d	Cohen’s d
Jump height (cm)	24.11 ± 3.05	24.34 ± 2.94	23.39 ± 1.76	-0.08	0.29	0.39
Maximum DCOM (cm)	23.62 ± 1.25 ^{§§}	26.66 ± 5.83 ^{###}	15.39 ± 1.55 ^{§§,##}	-0.72	5.85	2.64
Average Force (BW)	1.94 ± 0.12 [§]	1.87 ± 0.08 ^{###}	2.17 ± 0.12 ^{§,##}	0.69	-1.92	-2.94

Variables	Skaters (N = 8)	Volley (N = 8)	Ballet (N = 8)	Skaters– Volley	Skaters– Ballet	Volley– Ballet
	Mean ± sd	Mean ± sd	Mean ± sd	Cohen's d	Cohen's d	Cohen's d
Peak Force (BW)	2.36 ± 0.36	2.29 ± 0.23	2.77 ± 0.40	0.23	-1.08	-1.47
CI (BW · s)	0.227 ± 0.017	0.235 ± 0.008	0.223 ± 0.008	-0.60	0.30	1.50
CI duration (s)	0.242 ± 0.017 ^{*,§}	0.273 ± 0.023 ^{*,##}	0.193 ± 0.023 ^{§,##}	-1.53	2.42	3.48
Average power (W · kg⁻¹)	24.55 ± 2.84	23.94 ± 2.23 [#]	26.84 ± 1.91 [#]	0.24	-0.95	-1.40
Peak Power (W · kg⁻¹)	42.54 ± 2.61	42.02 ± 3.51	45.32 ± 2.35	0.17	-1.12	-1.10
Absolute K_{vert} (kN · m⁻¹)	5.07 ± 0.60 ^{§§}	4.89 ± 1.38 ^{##}	9.28 ± 1.94 ^{§§,##}	0.17	-2.93	-2.61
Normalized K_{vert} (kN · m⁻¹ · kg⁻¹)	0.098 ± 0.014 ^{§§}	0.089 ± 0.024 ^{##}	0.179 ± 0.037 ^{§§,##}	0.46	-2.90	-2.89

Note. Sd: standard deviation; CI: concentric impulse; DCOM: displacement of the centre of mass; BW: body weight; K_{vert}: vertical stiffness. *: Significant differences skaters–volley players ($p < 0.05$); **: Significant differences skaters–volley players ($p < 0.01$); §: Significant differences skaters–ballet dancers ($p < 0.05$); §§: Significant differences skaters–ballet dancers ($p < 0.01$); #: Significant differences volley players–ballet dancers ($p < 0.05$); ##: Significant differences volley players–ballet dancers ($p < 0.01$).

Significant differences between figure skaters and volleyball players were only found for the concentric impulse duration ($p < 0.05$). However, significant differences between figure skaters and ballet dancers were observed in the maximum displacement of the centre of mass, concentric impulse duration, absolute vertical stiffness, and normalised vertical stiffness ($p < 0.01$), as well as in average force ($p < 0.05$). Volleyball players and ballet dancers also showed significant differences in the maximum displacement of the centre of mass, average force, concentric impulse, concentric impulse duration, absolute vertical stiffness, and normalised vertical stiffness ($p < 0.01$), as well as in average power ($p < 0.05$).

The differences in absolute vertical stiffness and normalised vertical stiffness between the three groups are depicted in Figure 1.

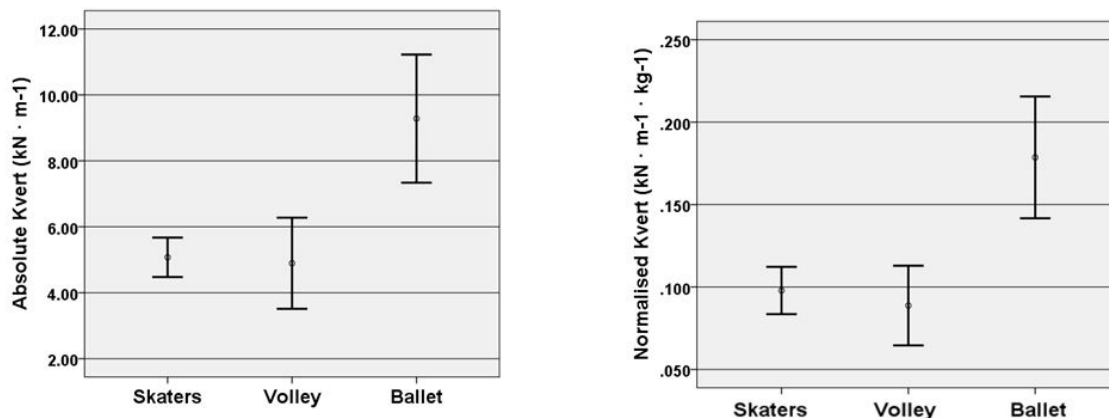


Figure 1. Absolute vertical stiffness (K_{vert}) and normalized vertical stiffness in the three groups (mean ± sd).

Discussion

The aim of this study was to assess the differences in the kinetic variables and vertical stiffness during a vertical jump in recreational female roller figure skaters, volleyball players, and ballet dancers aged 14–18 years. Although volleyball players achieved a greater vertical jump height (24.34 ± 2.94 cm) than figure skaters (24.11 ± 3.05 cm), and both groups achieved a greater vertical jump height than ballet dancers (23.39 ± 1.76 cm), these differences were not significant, and effect sizes were minimal or small. However, as it was hypothesised, the kinematic and kinetic mechanisms (and thus vertical stiffness) contributing to achieving those vertical jump heights were different, as it can be deduced by the significant differences found between groups in several variables.

The maximum displacement of the centre of mass was significantly smaller in ballet dancers (15.39 ± 1.55 cm) than in figure skaters (23.62 ± 1.25 cm) and volleyball players (26.66 ± 5.83 cm). This finding is in contrast to the results of Sánchez-Sixto et al. (2018), who stated that deep countermovements increased the net vertical impulse, leading to a greater jump height. In our study, the maximum displacement of the centre of mass for ballet dancers was not only much lower than that for figure skaters and volleyball players, but it was also much lower than that for volleyball players in studies by Sarvestan et al. (2018) and Rojano-Ortega et al. (2021), and that for sedentary participants in a study by Wang et al. (2004). However, Mandic et al. (2016) stated that in sports in which success depends not only on the jump height but also on the jumping quickness, athletes systematically selected a countermovement depth below the optimum value for maximizing vertical jump height. However, the lost magnitude of vertical jump height in a group of 11 elite male basketball players was only within the 0.1–1.2 cm range, and the jumps were markedly quicker. The same argument may be applied to ballet dancers because they must perform high jumps incorporated into the choreography (Brown et al., 2007; Kenne and Unnithan, 2008), and because the jumps are also aesthetic elements, they must be performed quickly; this forces the ballet dancers to execute jumps with a low displacement of the centre of mass.

To achieve similar jump heights with a lower displacement of the centre of mass, ballet dancers exerted significantly higher average values of VGRF (2.17 ± 0.12 BW) than figure skaters (1.94 ± 0.12 BW) and volleyball players (1.87 ± 0.08 BW). Combined with the smaller displacement of the centre of mass, this caused a significantly shorter concentric phase and, therefore, a shorter concentric impulse duration.

According to Linthorne (2001), the concentric impulse is the main factor responsible for take-off velocity and, therefore, jump height; this notion was empirically supported by Kirby et al. (2011), who observed an almost perfect significant correlation between concentric impulse and jump height in a CMJ ($R = 0.925$, $p < 0.0001$). In the present study, no significant differences were found in concentric impulse between the three groups; however, the p -value was 0.063 for the pairwise comparison between volleyball players and ballet dancers, and the effect size was greater than 0.5, indicating a clinically meaningful difference. Nevertheless, this difference was not large enough for the jump height to be significantly greater in volleyball players than in ballet dancers.

Ballet dancers exhibited an average power value (26.84 ± 1.91 W · kg⁻¹) greater than that of figure skaters (24.55 ± 2.84 W · kg⁻¹) and volleyball players (23.94 ± 2.23 W · kg⁻¹) with significant differences only found for the pairwise comparison between volleyball players and ballet dancers. However, no significant differences in peak power were found between groups. These results are in accordance with those of Harman et al. (1990), who found a strong correlation between peak power and vertical jump height ($R = 0.88$, $p \leq .05$). Accordingly, because no significant differences were observed between groups for vertical jump height in our study, peak power did not differ significantly between groups.

Because ballet dancers exerted more force than the other two groups and the vertical displacement of their centre of mass was lower, their absolute vertical stiffness value was significantly higher (9.28 ± 1.94 kN · m⁻¹) than that of figure skaters (5.07 ± 0.60 kN · m⁻¹) and volleyball players (4.89 ± 1.38 kN · m⁻¹), whereas no significant differences and minimal effect sizes were observed between these two groups. Similar results were found for normalised vertical stiffness.

The results for figure skaters and volleyball players appear to contradict previous studies that have stated that higher levels of lower-extremity stiffness are predictive of higher maximum vertical jump heights (Brughelli and Cronin, 2008; Goodwin et al., 2019; Serpell et al., 2012; Waxman et al., 2018). By contrast, both the absolute and normalised values for ballet dancers were much higher than those for figure skaters and volleyball players. These results may indicate that ballet dancers are highly impulsive because they must perform quicker jumps than figure skaters and volleyball players, and they may have developed a jumping technique that makes better use of the stretch–shortening cycle in the CMJ. However, these high vertical stiffness values may also increase the ballet dancers' risk for lower-extremity injury and future research on this subject is needed.

This study is one of the few studies to investigate kinetic variables and vertical stiffness in adolescent female athletes from different high-intensity intermittent disciplines, which is the key strength of the study. This study's main limitation is the relatively small number of participants in each group, which may reduce the statistical power of the research.

Conclusions

Our results showed that adolescent Andalusian female figure skaters and volleyball players did not present significant differences in any of the measured variables, showing that their kinematic and kinetic mechanisms and their vertical stiffness contributing to CMJ performance were similar. However, female ballet dancers had lower values of vertical displacement of the centre of mass, lower values of the concentric phase duration, and higher values of average VGRF. These results suggest that female ballet dancers are more impulsive than female figure skaters and volleyball players. In addition, their higher vertical stiffness may indicate better use of the stretch–shortening cycle and could be the cause or the effect of this high impulsiveness. Specific trainings, including plyometric exercises, could enhance vertical stiffness in figure skaters and volleyball players, increasing their explosiveness and, therefore, their vertical jump height.

Disclosure statement

The authors declare no conflict of interest.

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