SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

ORIGINAL ARTICLE

Effect of hurdle height on neuromuscular activity during bilateral jumps in female athletes and physical education students

Emmanuel Nicolás Ignacio Morales ✉ . *University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.*
Darío Fernando Cappa. *University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.*
Ezequiel Aquistapace. *University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.*
Leandro Nodari. *University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.*
Marco Ramos. *University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.*

ABSTRACT

This study aimed to evaluate the neuromuscular performance of hurdle jumps at different obstacle heights in women to identify the hurdle height eliciting the highest neuromuscular demands. Participants included two groups of regional-level athletes, field hockey players (HOC) and track and field athletes (TAF), and a group of physical education students (PE). Assessments consisted of the countermovement jump with arm swing (CMJA) and hurdle jumps at 60%, 80%, and 100% of CMJA height performed on a force platform. Electromyographic (EMG) activity of the medial gastrocnemius (GM) and tibialis anterior (TA) was recorded, and force variables were analyzed. Rate of force development (RFD) and vertical stiffness (Kvert) were calculated. Results indicated that RFD was significantly greater at 100% of CMJA height, regardless of the group analyzed. EMG activity of the GM was also higher at 100% CMJA height, while no significant differences were observed for the TA. Kvert was not sensitive to hurdle height. In conclusion, 100% of CMJA height is the hurdle height eliciting the greatest neuromuscular and force–time demands in women, independent of sport background.
Keywords: Physical education, Plyometrics, Hurdle jumps, Neuromuscular activity, Force–time curve, Stretch–shortening cycle.

Cite this article as:
Morales, E. N. I., Cappa, D. F., Aquistapace, E., Nodari, L., & Ramos, M. (2026). Effect of hurdle height on neuromuscular activity during bilateral jumps in female athletes and physical education students. *Scientific Journal of Sport and Performance*, *5*(3), 482-492. https://doi.org/10.55860/KEMR9640

✉ **Corresponding author.** *University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.*
E-mail: enig_mor_91@hotmail.com
Submitted for publication March 11, 2026.
Accepted for publication April 06, 2026.
Published May 07, 2026.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/KEMR9640

INTRODUCTION

Plyometric training is of vital importance to optimally enhance overall muscle power and specific competitive actions. Jumps, throws, strikes, and sprints are considered short stretch-shortening cycle sports actions (Schmidtbleicher, 1992). These exercises are characterized by the development of high velocity at the end of the concentric phase of the movement (Newton, Robert U. ; McEvoy, 1994).

Loturco et al. (Loturco et al., 2023) and Healy et al. (Healy et al., 2021) surveyed sports coaches and found that 89% and 93%, respectively, employed hurdle jumps, positioning this exercise as one of the most important in the plyometric method to improve sprint power. Hurdles are considered an obstacle, and their height is thus an important variable that influences the intensity of the exercise.

Several studies have described the neuromuscular characteristics of two-legged hurdle jumps (Cappa & Behm, 2013; Healy et al., 2020; Janikov et al., 2023; Kossow & Ebben, 2018). However, many of these studies used male samples. Heick et al. (Heick et al., 2020) used a mixed sample but did not identify sex-based differences. Kossow et al. (Kossow & Ebben, 2018) suggested there are no differences between men and women when analysing single hurdle jumps at fixed heights of 45 cm. However, in this research, the vertical and horizontal strength levels observed were very low, suggesting that the jumps were not continuous, as they are typically performed in training.

Regarding hurdle height, no studies have analysed multiple obstacle heights in women. A previous study on hurdle jumps investigated men using obstacles at 100%, 120%, 140%, and 160% of the maximum height reached in a countermovement jump with arm swing (CMJA). The rate of force development showed that the optimal height was 100%, with higher heights not adding intensity. This was evident when analysing two key variables: contact time increased by 18% when hurdle height rose from 100% to 160% (from 177 to 209 ms, respectively), while force decreased by 6.9% (from 4305 to 4007 N) (Cappa & Behm, 2013). This indicates that excessively increasing hurdle height above the maximum CMJA performance does not enhance the intensity of the motor action.

During plyometric activities, the lower limbs behave like a spring (Farley et al., 1991). Depending on the movement type and intensity used, the neuromuscular system adjusts limb stiffness to increase power. For instance, Farley found that greater execution speed increases muscle stiffness. High execution speed also ensures short ground contact times (Farley & Morgenroth, 1999).

To achieve high levels of stiffness, ranges of motion with small flexion-extension degrees at the hip, knee, and ankle should be used, as shown in sprint analysis at different speeds (Kuitunen et al., 2002). This facilitates the proper use of elastic energy stored during the contact phase (Wilson et al., 1991). Kuitunen demonstrated that vertical stiffness increases significantly (+40%) when sprint speed rises from 70% to 90% of maximum speed.

Arampatzis (Arampatzis et al., 2006) analysed drop jumps from various heights and confirmed that maximum power is achieved with high lower limb stiffness. In this study, athletes were asked to voluntarily modify ground contact times, decreasing and increasing them twice to create five groups. Leg stiffness increased when ground contact time was reduced but worsened when it was increased. However, maximum power at all drop heights was observed when athletes gave their best effort. This suggests there is an optimal stiffness level for the lower limbs to maximise mechanical power, which is self-regulated and decreases when modified voluntarily.

In this sense, when hurdle height exceeds maximum CMJA performance, the subject must increase lower limb flexion, which conditions jump execution by raising the centre of gravity. Therefore, hurdle height plays a critical role in generating stiffness.

Although recommendations for determining hurdle height exist, these are based on male data. In highly explosive actions such as sprinting, women exhibit slightly longer contact times than men (~+7%). Consequently, it is possible that hurdle heights for jumps may differ from those recommended for men. Therefore, the objective of this study was to analyse neuromuscular performance at different hurdle heights in active women.

METHODS

Thirty-eight female participants categorized into three distinct groups based on their training background: Physical Education students (PE, n = 14, age 23.67 ± 2.67, mass 60.98 ± 9.75 kg, height 159.17 ± 5.42 cm and BMI 24.01 ± 3.28), Field Hockey (HOC, n = 12, age 22.42 ± 1.77, mass 61.38 ± 8.91 kg, height 160.84 ± 6.39 cm and BMI 23.70 ± 2.94) and Track and Field (TAF, n = 12, age 21.18 ± 2.97, mass 60.07 ± 9.10 kg, height 162.64 ± 6.80 cm and BMI 22.65 ± 2.60) athletes. Sports volunteers had a minimum of 3 years of sports experience and a strength training frequency of at least 3 times per week for the past year. Inclusion criteria for non-sporting subjects were being physically active and not participating in competitive sports. All subjects were familiar with plyometric and explosive jump training. The exclusion criterion was having disabling injuries in the last 6 months or at the time of testing. Written informed consent was obtained from the subjects before study participation. This study was conducted in accordance with the principles of the Declaration of Helsinki (World Medical Asociation, 2013). This study was approved by the University Institute of Physical Education from Mendoza (Argentina) committee of research.

Procedures

Vertical jump testing

The warm-up consisted of 4 minutes on a bicycle ergometer (50 watts of power), lumbar and abdominal hyperextension exercises (3 sets of 10 repetitions), a series of squats of 10 repetitions with 20 kg of overload, sub maximum vertical jump without arm swing (2 sets of 5 repetitions), sub maximum rebounds (2 sets of 10 repetitions), maximum rebounds (2 sets of 10 repetitions) and hurdle jumps at a height between 10 and 20 cm (2 sets of 4 repetitions). For the evaluation of the vertical jump, the subjects were placed on 2 force platforms (one for each foot) brand PASCO Scientific 2-axis PS-2142, with sampling frequency of 1000 Hz. They were then asked to perform a maximal vertical jump with swing of arms (CMJA). The height reached was calculated using the formula: CMJA height (cm) = $(t^2 \cdot g) / 8$, where t is flight time and g is acceleration due the gravity. Two maximum attempts were made, and the highest value was selected. Then, was calculated 60 and 80 percent of the height of CMJA to use with hurdles jump evaluation.

Hurdle jumping testing

After the CMJA evaluation, the subjects were instructed on the hurdles test. Four hurdles were placed on a slide, aligned and separated from each other according to the participants' preference. The force platforms were located between the 2nd and 3rd hurdles as in Cappa and Behm (Cappa & Behm, 2011) (see Figure 1). During both jumps, neuromuscular activation was collected through EMG data using a Wireless electromyograph (biosignalsplux Explorer Biosignals S.A.). Electrodes (Medi-Trace MT200 Kendall™, Technical products, Toronto, Ontario, Canada) were placed on the GM and TA of the subjects' right leg according to SENIAM guidelines (Stegeman & Hermens, 2007). Raw data collection was performed with OpenSignals software (version 2.0.0). Processing of this data was performed with MatLab R2018b (The

MathWorks, Inc.) and a band-pass Butterworth filter (20–450 Hz, 6th order), with a 50-Hz notch filter applied to remove power line noise. Subjects were instructed to perform the jumps as quickly as possible, minimizing contact time on the platforms. No technique was specified to overcome the fences. Subjects were only verbally encouraged to take the test as quickly as possible. Two attempts were performed with a 1-minute rest between each to avoid fatigue. Contact and take-off with the force platforms were strictly monitored, and if in any attempt a delay in the shortening-stretching cycle was observed or if the subjects fell off the platforms, the attempt was repeated. If a difference in performance of more than 10% was found, a third attempt was made. The EMG signal was analysed at 2 moments: during pre-activation, 100 milliseconds before ground contact (PRE) and during ground contact time (CON). The protocol was repeated at 60, 80 and 100% of the maximum height of the CMJA, in random order between trials for each hurdle height. The selected hurdle heights were chosen to represent progressively increasing relative intensities commonly used in plyometric training. Heights below 60% of CMJA were not considered, as pilot observations and previous literature suggest that such low obstacles do not elicit sufficient neuromuscular demand to differentiate force–time or EMG responses from low-intensity rebound jumps.

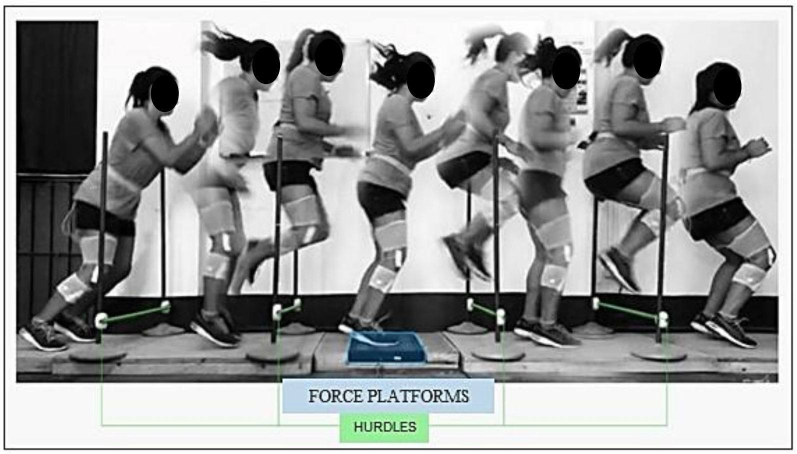


Figure 1. Hurdles jump testing.

Statistical analysis

During the CMJA test and Hurdles jumps, the following raw data were collected: peak vertical force (PF, N), average vertical force (AF, N), contact time (CT, s), and flight time (FT, ms). Derived variables included: normalized peak vertical (nPF, N·N-1), normalized average vertical force (nMF, N·N-1), rate of force development (RFD, N·s-1), normalized rate of force development (nRFD, N·s-1·N-1), mechanical power (POT, W), normalized power (nPOW, W·N-1) and vertical stiffness (Kvert, kN·m-1). Mechanical power was computed using the Sayers equation (Sayers et al., 1999). Normalized variables were calculated using the body weight. Peak rate of force development (RFD) was computed as the maximal slope of the force–time curve during ground contact (ΔF/Δt), expressed in $N·s^{-1}$. Normalized RFD (nRFD) was obtained by dividing RFD by body mass ($N·s^{-1}·kg^{-1}$). Kvert was estimated using the spring–mass model: Kvert = $m (2\pi f)^2$, where m is body mass and f is the natural frequency of oscillation estimated from contact/flight times (Mc Mahon, Thomas, Cheng, 1990). EMG data collected during hurdle jumps were normalized to the corresponding CMJA EMG activity (set at 100%). EMG signals obtained during hurdle jumps were normalized to the corresponding CMJA EMG activity. This approach was selected because CMJA represents a maximal dynamic task with similar neuromuscular and stretch–shortening cycle characteristics to hurdle jumps.

Statistical treatment

Statistical analyses were performed using JASP v0.19 and MS Excel 365. Normality was checked with Shapiro–Wilk. Normally distributed variables were analysed with one-way ANOVA (between groups) and repeated-measures ANOVA (within subjects); Bonferroni adjustments were used for post-hoc pairwise comparisons. Non-normal variables were tested with Kruskal–Wallis (with Dunn post-hoc) or Mann–Whitney U as appropriate. Effect sizes are reported as eta-squared (η^2) for ANOVA and Cohen's d for pairwise contrasts; for non-parametric tests report eta-squared (η^2) or Kendall's W. The level of significance was set at *$p < .05$; **$p < .01$; ***$p < .001$.

RESULTS

A Kruskal-Wallis test revealed a significant difference in age between the PE and TAF groups (H = 6.578, rank $\eta^2 = 0.131$, 95% CI: 0.000, 0.512, $p = .037$). Post-hoc analysis using the Mann-Whitney U test indicated that participants in the PE group were significantly older than those in the TAF group (z = 2.56, $p = .031$). No other significant differences were found between the groups.

Table 1 shows the mean (±SD) of the variables of the force-time curve of the CMJA test for each group. The statistical analysis revealed significant differences in CMJA height (F = 15.40, $\eta^2 = 0.468$, 95% CI: 0.209, 0.635, $p < .001$). Post-hoc analysis indicated that the TAF group had significantly higher CMJA height compared to both the PE (t = -5.496, d = -2.162, 95% CI: -3.345, -0.978, $p_{bonf} < .001$) and HOC (t = -3.517, d = -1.436, 95% CI: -2.549- -0.322, *pbonf* = .004) groups.

Average force normalized by body weight also differed significantly between groups (F = 5.328, $\eta^2 = 0.239$, 95% CI: 0.019, 0.446, $p = .01$). Post-hoc tests showed that the HOC group had significantly higher values than the TAF group (t = 3.157, 95% CI: 0.021, 0.19, *pbonf* = .01).

Power normalized by body weight significantly differed among groups (H = 15.49, rank $\eta^2 = 0.397$, 95% CI: 0.236, 0.618, $p < .001$). Post-hoc Mann-Whitney U tests indicated that the TAF group had higher values compared to both PE (z = -3.927 [Wj = 11.786, Wi = 28.909], *pbonf* < .001) and HOC (z = -2.341 [Wj = 18.333, Wi = 28.909], $p = .019$) groups.

No other significant differences were found between the groups. A significant interaction between hurdle height and force-time curve variables was observed when hurdles were set at 100% vertical jump height (As shown in Table 2).

Peak vertical force was significantly higher at 100% hurdle height compared to both 60 and 80% ($X^2 = 10.865$, $p = .004$). ANOVA post hoc analysis showed that 100% > 60% (T-stat = 3.352, [Wi = 63.00, Wj = 90.00], *pbonf* = .004) and 100% > 80% (T-stat = 2.607, [Wi = 69.00, Wj = 90.00], *pbonf* = .033). Similarly, normalized peak vertical force was significantly greater at 100% (F = 7.813, $p < .001$, $\eta^2 = 0.187$) compared to 60% (t = -3.901, d = -0.749, 95% CI: [-0.774, -0.167], *pbonf* = .001).

Mean vertical force also showed significant differences (F = 6.970, $p = .002$, $\eta^2 = 0.162$), with 100% exceeding both 60% (t = -3.045, d = -0.416, 95% CI: [-171.191, -16.463], *pbonf* = 0.013) and 80% (t = -3.440, d = -0.381, 95% CI: [-148.645, -23.203], *pbonf* = 0.004). Consistent patterns were observed for normalized mean vertical force (F = 5.961, $p = .004$, $\eta^2 = 0.139$) where 100% was greater than 60% (t = -3.084, d = -0.450, 95% CI: [-0.294, -0.030], *pbonf* = 0.012) and 80% (t = -2.720, d = -0.363, 95% CI: [-0.252, -0.010], *pbonf* = 0.03).

Rate of force development was significantly higher at 100% (X^2 = 10.343, *p* = .006) compared to both 60% (T-stat = 2.425, [Wi = 66.00, Wj = 85.00], *pbonf* = .036) and 80% (T-stat = 3.318, [Wi = 59.00, Wj = 85.00], *pbonf* = .004) with similar results for normalized RFD (X^2 = 10.343, *p* = .006) where 100% was over 60% (T-stat = 2.425, [Wi = 66.00, Wj = 85.00], *p* = .018) and 80% (T-stat = 3.318, [Wi = 59.00, Wj = 85.00], *pbonf* = .004). Vertical stiffness (Kvert) did not differ significantly across hurdle heights (*p* > .05).

Table 1. CMJA variables (Mean ± SD).

	PE	HOC	TAF
CMJA height (cm)	27.71 ± 3.3	30.75 ± 4.7	36.75 ± 4.5 $^{a***\ b**}$
Contact time (s)	0.94 ± 0.12	0.93 ± 0.18	1.00 ± 0.14
Average force (N)	731 ± 89	750 ± 80	718.4 ± 97
Normalized average force ($N·N^{-1}$)	1.27 ± 0.07	1.30 ± 0.07 ^{c*}	1.19 ± 0.10
Peak force (N)	1348 ± 214	1431 ± 236	1403 ± 257
RFD ($N·s^{-1}$)	1686 ± 497	1805 ± 582	1633 ± 384
Normalized RFD ($N·s^{-1}·N^{-1}$)	2.80 ± 0.60	3.13 ± 1.03	2.83 ± 0.88
K_{vert} ($N·m^{-1}$)	2.41 ± 0.89	2.60 ± 0.93	2.47 ± 0.98
Power (W)	2419 ± 410	2599 ± 553	2803 ± 459 $^{d***\ e*}$
Normalized power ($W·N^{-1}$)	4.05 ± 0.22	4.29 ± 0.45	4.69 ± 0.27

*Note. CMJA = countermovement jump with arms swing. TAF = Track and Field; HOC = Field Hockey; PE = Physical Education. a: TAF vs PE; b: TAF vs HOC; c: HOC vs TAF; d: TAF vs PE; e: TAF vs HOC. * p < .05; ** p < .01; *** p < .001.*

Table 2. Analysis of hurdles jump (Mean ± SD).

	Hurdles heights as a percentage of maximum CMJA		
	60%	80%	100%
Contact Time (s)	0.164 (0.02)	0.166 (0.02)	0.165 (0.02)
Peak Vertical Force (N)	3122 (459)	3101 (467)	3335 (364) $^{a**\ b*}$
Normalized Peak Vertical Force ($N·N^{-1}$)	5.15 (0.55)	5.34 (0.83)	5.73 (0.68) ^{c**}
Mean Vertical Force (N)	1654 (262)	1645 (233)	1740 (203) ^{d**}
Normalized Mean Vertical Force ($N·N^{-1}$)	2.79 (0.34)	2.82 (0.37)	2.95 (0.37) ^{e*}
RFD ($N·s^{-1}$)	51652 (15773)	51090 (18496)	56259 (13356) $^{f**\ g*}$
Normalized RFD ($N·s^{-1}·N^{-1}$)	87.37 (27.63)	87.18 (33.01)	95.57 (24.32) $^{h*\ i***}$
K_{vert} ($N·m^{-1}$)	38.37 (8.29)	39.42 (13.76)	36.08 (9.03)

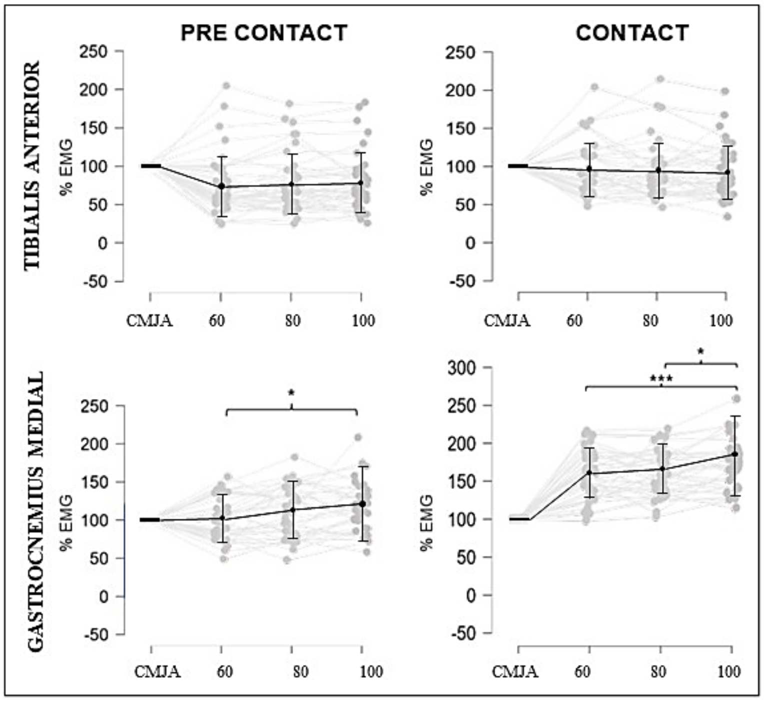
*Note. RFD = Rate Force Development. Kvert = Vertical Stiffness. a: 100% > 60%; b: 100% > 80%; c: 100% > 60%; d: 100% > 60 and 80%; e: 100% > 60 and 80%; f: 100% > 60%; g: 100% > 80%; h: 100% > 60%; i: 100% > 80%. * p < .05; ** p < .01; *** p < .001.*

No statistical differences were found in force-time variables when comparing between groups, nor when comparing athletes and students (*p* > .05).

A significant difference was observed between CMJA and hurdle jumps in the PRE activity of the TA (*p* < .001) and CON activity of the GM (*p* < .001) for all heights. No statistically significant differences were found between CMJA and hurdle jumps in the CON activity of the TA or the PRE activity of the GM.

Repeated measures ANOVA (see Figure 2) revealed significant differences between hurdle heights for the pre-contact activity of the GM (χ^2 = 9.842, *p* = .02) and the ground contact activity of the GM (χ^2 = 65.612, *p* < .001).

Specifically, for the PRE activity of the GM, the 100% hurdle height condition showed significantly greater activity compared to the 60% condition (T-stat = 2.928, W_i = 73.0, W_j = 103.5; *pBonf* = .025). For the CON activity of the GM, the 100% hurdle height condition showed significantly greater activity compared to both the 60% condition (T-stat = 4.183, W_i = 90.0, W_j = 117.0; *pBonf* < .001) and the 80% condition (T-stat = 2.944, W_i = 98.0, W_j = 117.0; *pBonf* = .024).



*Note. *p < .05; **p < .01; ***p < .001.*

Figure 2. EMG of hurdles jumps.

Analyses of EMG by groups revealed a significant difference in the contact phase of GM at 100% (Kruskal-Wallis = 8.051, *p* = .018, η^2 = 0.178). Post hoc pairwise comparisons indicated that the TAF subgroup exhibited a significantly higher activation of GM in contact phase than the HOC group (z = -2.803, *p* = .015). No other significant differences were found in the analysis.

DISCUSSION

The manipulation of training intensity is fundamental for programming and undulating workload distribution. In hurdle jumps, hurdle height is a key variable to establish exercise intensity (Cappa & Behm, 2013; Jensen & Ebben, 2007). The main finding of this study was that rate of force development (RFD) was significantly greater at 100% of CMJA height compared with 60% and 80%, when analysing the overall sample. However, when groups were analysed separately, no significant differences were found. This is likely explained by the fact that all groups maintained low ground contact times as hurdle height increased, while relative force production increased slightly. Notably, at 100% CMJA height, all groups exhibited the highest relative force and the lowest contact times (Table 1). Thus, RFD at 100% CMJA height was consistently greater, although in some cases it did not reach statistical significance.

Although hurdle jumps are widely used by coaches to develop lower-limb power (Healy et al., 2021), the most appropriate method to determine training intensity and movement specificity remains unclear. In male athletes, Cappa and Behm (Cappa & Behm, 2011) reported that the optimal hurdle height corresponded to the maximum height achieved in the countermovement jump with arm swing (CMJA). Higher hurdle heights required increased flexion to clear the obstacle, which raised the centre of mass, led to longer ground contact times, and reduced peak force. Consequently, RFD decreased when hurdle height exceeded 100% CMJA. For example, RFD decreased by approximately 21% when comparing 100% with 160% CMJA (40,981 vs. 32,153 $N \cdot s^{-1}$).

In contrast, the present study analysed hurdle heights below maximal CMJA performance. Our results showed that reducing hurdle height below 100% CMJA led to significant decreases in RFD both in pooled analyses and when groups were compared independently (Figure 2, Table 1).

Regarding muscle stiffness (Kvert), no significant differences were observed across hurdle heights. This result was unexpected, given that increases in RFD are typically associated with increases in stiffness. Arampatzis et al. (Arampatzis et al., 2001), however, demonstrated in drop jumps that increases in stiffness may occur simultaneously with decreases in power output. In their study, when athletes were instructed to minimize ground contact time, stiffness remained elevated but power decreased. These findings suggest that stiffness adaptations may not always translate into enhanced performance. Furthermore, Kvert has limitations as a performance indicator, particularly for horizontal displacements (Maloney & Fletcher, 2021), and it does not account for the summation of joint-specific stiffness.

The calculation method also influences stiffness outcomes. Kvert, based on a spring-mass model (Mc Mahon, Thomas, Cheng, 1990), reflects whole-body stiffness relative to centre-of-mass displacement. However, ankle and knee joints may adopt distinct strategies to modulate stiffness during hurdle jumps. Farley and Morgenroth (Farley & Morgenroth, 1999) reported that ankle modulation is the primary mechanism for adjusting stiffness in vertical hopping, while knee contribution is more limited. When an external obstacle requires additional flexion to clear, stiffness regulation may differ from vertical hopping strategies.

It should be noted that Kvert, as derived from the spring–mass model, represents a global measure of lower-limb stiffness and does not capture joint-specific adaptations. During hurdle jumps, ankle and knee joints may adopt different stiffness regulation strategies depending on obstacle height, which may not be reflected in whole-body Kvert values. Consequently, the lack of sensitivity observed for Kvert across hurdle heights may be partly explained by methodological limitations inherent to this model.

Peak force values during hurdle jumps were significantly higher than during CMJA (3,400 vs. 1,400 N, respectively), likely due to the high pre activation and force requirements of hurdle clearance. Similar findings have been reported in box jumps in female handball players (Koefoed et al., 2022), where increasing box height above ~70% of CMJA did not significantly increase power output, as athletes compensated primarily by flexing the legs rather than producing higher propulsive forces.

From a training perspective, while maximal strength development is typically prescribed at 80–100% of 1RM in exercises such as squats, ballistic multi-jump actions such as hurdle jumps provide a more physiologically maximal expression of force. For instance, Perttunen et al. (Perttunen et al., 2000) reported peak forces exceeding 10,000 N in male triple jumpers, values that far surpass those observed in closed-chain resistance training. Although sex differences exist, female athletes achieve ~85% of male world record performance in this discipline, reinforcing the high neuromuscular demands of jumping-based exercises. In the present study, hurdle jumps produced forces that were double or even triple those observed in CMJA.

Electromyographic analyses revealed that GM activity increased with hurdle height, particularly during ground contact (+10%) and concentric phase (+24%), coinciding with an 8% increase in concentric force. TA activity remained relatively constant across hurdle heights, consistent with prior reports (Cappa & Behm, 2013). When analysed by training background, no group differences were found, suggesting that 100% CMJA hurdle height optimizes neuromuscular output independently of sport specialization.

These findings have practical implications. Many training programs employ fixed commercial hurdle heights (15–20 cm) for group sessions. However, such standardization may underestimate or misrepresent the optimal intensity for individual athletes. Using individualized hurdle heights based on CMJA performance ensures that athletes train at an intensity that maximizes neuromuscular output.

A limitation of the present study is the modest sample size in subgroup analyses (n = 12–14), which may have reduced statistical power to detect interaction effects. Additionally, EMG signals were recorded unilaterally (right leg), and kinematic measures were not collected; future studies should include bilateral EMG and motion capture to elucidate joint-specific strategies. Additionally, vertical stiffness was estimated using a spring–mass model, which does not account for joint-specific stiffness regulation; therefore, potential adaptations at the ankle or knee level may not have been detected.

CONCLUSION

In conclusion, RFD was greatest at hurdle heights equivalent to 100% of CMJA performance. Lower hurdle heights were associated with reduced neuromuscular variables. Vertical stiffness (Kvert) was not sensitive to changes in hurdle height, suggesting that alternative methods may be required to assess stiffness during hurdle jumps. Practically, prescribing hurdle height relative to each athlete's CMJA rather than using fixed commercial standards appears to be the eliciting the highest neuromuscular demands strategy for maximizing neuromuscular performance in women.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Emmanuel N. I. Morales. Methodology: Emmanuel N. I. Morales; Dario F. Cappa. Formal analysis: Emmanuel N. I. Morales. Investigation: Emmanuel N. I. Morales; Dario F. Cappa; Ezequiel Aquistapace; Leandro Nodari; Marco Ramos. Data curation: Emmanuel N. I. Morales; Ezequiel Aquistapace. Writing – original draft: Emmanuel N. I. Morales. Writing – review & editing: Dario F. Cappa; Emmanuel N. I. Morales. Supervision: Dario F. Cappa. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Arampatzis, A., De Monte, G., Karamanidis, K., Morey-Klapsing, G., Stafilidis, S., & Brüggemann, G. P. (2006). Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. Journal of Experimental Biology, 209(17), 3345-3357. https://doi.org/10.1242/jeb.02340

Arampatzis, A., Schade, F., Walsh, M., & Brüggemann, G. P. (2001). Influence of leg stiffness and its effect on myodynamic jumping performance. Journal of Electromyography and Kinesiology, 11(5), 355-364. https://doi.org/10.1016/S1050-6411(01)00009-8

Cappa, D. F., & Behm, D. G. (2011). Training specificity of hurdle vs. countermovement jump training. Journal of Strength and Conditioning Research, 25(10), 2715-2720. https://doi.org/10.1519/JSC.0b013e318208d43c

Cappa, D. F., & Behm, D. G. (2013). Neuromuscular characteristics of drop and hurdle jumps with different types of landings. Journal of Strength and Conditioning Research, 27(11), 3011-3020. https://doi.org/10.1519/JSC.0b013e31828c28b3

Farley, C. T., Blickhan, R., Saito, J., & Taylor, C. R. (1991). Hopping frequency in humans: A test of how springs set stride frequency in bouncing gaits. Journal of Applied Physiology, 71(6), 2127-2132. https://doi.org/10.1152/jappl.1991.71.6.2127

Farley, C. T., & Morgenroth, D. C. (1999). Leg stiffness primarily depends on ankle stiffness during human hopping. Journal of Biomechanics, 32(3), 267-273. https://doi.org/10.1016/S0021-9290(98)00170-5

Healy, R., Bolger, R., Kenny, I. C., & Harrison, A. J. (2020). Kinematic Differences Between Sprinting and the Hurdle Jump Exercise - a Preliminary Analysis. 38th International Society of Biomechanics in Sport Conference, 520-523.

Healy, R., Kenny, I. C., & Harrison, A. J. (2021). Resistance training practices of sprint coaches. Journal of Strength and Conditioning Research, 35(7), 1939-1948. https://doi.org/10.1519/JSC.0000000000002992

Heick, J. D., Talkington, M., & Jain, T. (2020). Electromyographic Analysis of Gluteal Recruitment: an Exploration of Activation During Jumping Tasks. International Journal of Sports Physical Therapy, 15(6), 1019-1028. https://doi.org/10.26603/ijspt20201019

Janikov, M. T., Pádecký, J., Doguet, V., & Tufano, J. J. (2023). Countermovement, Hurdle, and Box Jumps: Data-Driven Exercise Selection. Journal of Functional Morphology and Kinesiology, 8(2). https://doi.org/10.3390/jfmk8020061

Jensen, R. L., & Ebben, W. P. (2007). Quantifying plyometric intensity via rate of force development, knee joint, and ground reaction forces. Journal of Strength and Conditioning Research, 21(3), 763-767. https://doi.org/10.1519/R-18735.1

Koefoed, N., Dam, S., & Kersting, U. G. (2022). Effect of Box Height on Box Jump Performance in Elite Female Handball Players. Journal of Strength and Conditioning Research, 36(2), 508-512. https://doi.org/10.1519/JSC.0000000000003481

Kossow, A. J., & Ebben, W. P. (2018). Kinetic analysis of horizontal plyometric exercise intensity. Journal of Strength and Conditioning Research, 32(5), 1222-1229. https://doi.org/10.1519/JSC.0000000000002096

Kuitunen, S., Komi, P. V., & Kyröläinen, H. (2002). Knee and ankle joint stiffness in sprint running. Medicine and Science in Sports and Exercise, 34(1), 166-173. https://doi.org/10.1097/00005768-200201000-00025

Loturco, I., Pereira, L. A., Freitas, T. T., Moura, T. B. M. A., Mercer, V. P., Fernandes, V., Moura, N. S. A., Moura, N. A., Zajac, A. A., & Bishop, C. (2023). Plyometric Training Practices of Brazilian Olympic Sprint and Jump Coaches: Toward a Deeper Understanding of Their Choices and Insights. Journal of Human Kinetics, 88(July), 131-150. https://doi.org/10.5114/jhk/169167

Maloney, S. J., & Fletcher, I. M. (2021). Lower limb stiffness testing in athletic performance: a critical review. Sports Biomechanics, 20(1), 109-130. https://doi.org/10.1080/14763141.2018.1460395

Mc Mahon, Thomas, Cheng, G. (1990). The Mechanics of Running: How does Stiffness Couple With Speed? In J Biomechanics (Vol. 23, pp. 65-78). https://doi.org/10.1016/0021-9290(90)90042-2

Newton, Robert U. ; McEvoy, K. P. (1994). Baseball Throwing Velocity: A Comparison of Medicine Ball Training and Weight Training. Journal of Strength and Conditioning Research, 8(3), 198-203. https://doi.org/10.1519/1533-4287(1994)008<0198:BTVACO>2.3.CO;2

Perttunen, J., Kyröläinen, H., Komi, P. V., & Heinonen, A. (2000). Biomechanical loading in the triple jump. Journal of Sports Sciences, 18(5), 363-370. https://doi.org/10.1080/026404100402421

Sayers, S. P., Harackiewicz, D. V., Harman, E. A., Frykman, P. N., & Rosenstein, M. T. (1999). Cross-validation of three jump power equations. Medicine and Science in Sports and Exercise, 31(4), 572-577. https://doi.org/10.1097/00005768-199904000-00013

Schmidtbleicher, D. (1992). Training for power event. In: Komi PV (ed) Strength and power in sport. Blackwell Scientific, London, pp 381-395. Retrieved from: The School Review.

Wilson, G. J., Elliott, B. C., & Wood, G. A. (1991). The effect on performance of imposing a delay during a stretch-shorten cycle movement. In Medicine and Science in Sports and Exercise (Vol. 23, Issue 3, pp. 364-370). https://doi.org/10.1249/00005768-199103000-00016

World Medical Asociation. (2013). Declaración de Helsinki de la AMM - Principios éticos para las investigaciones médicas en seres humanos. World Medical Association, Inc, 81(3), 1-8. https://doi.org/10.1001/jama.2013.281053