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ORIGINAL ARTICLE

Correlations Between Jump Height, Ground Contact Time, and Athletic Performance Indicators in Jump Landing Tasks

[1]Maolin Dong♣, [2]Youngsuk Kim♣, [2]Yanjia Xu, [2]Bin Zhu, [3]Ming Li*, [2]Sukwon Kim*

[1]College of Wushu, Henan University, Zhengzhou, China. [2]Department of Physical Education, Jeonbuk National University, Jeonju, Korea. [3]Department of Physical Education, Yantai University, Yantai, China.

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ABSTRACT

Background. Jump landing tasks are frequently employed as a non-specific tool to quantify the capabilities of the lower extremity performance and athletes' injuries. **Objectives.** This study aimed to investigate the relationships between jump height (JH) and ground contact time (CT) in countermovement jump (CMJ) and drop jump (DJ) with assessment indicators such as reactive strength index (RSI), eccentric phase rate of force development (ERFD), peak rate of force development (PRFD), average velocity (EV), amortization phase time (AT), peak ground reaction force (PF), concentric phase average force (CAF), and vertical stiffness. **Methods.** This study was cross-sectional, with 23 participants completing CMJ and DJ tests. Ground reaction force and center of mass displacement data were captured using a motion system and force platforms. Paired-sample t-tests were used to compare differences between CMJ and DJ in JH, CT, ERFD, RSI, and CAF. Spearman rank correlation analysis was conducted to examine the correlation between vertical stiffness and other variables, while Pearson product-moment correlation was used to identify correlations among other variables. **Results.** JH was comparable between CMJ and DJ (p=0.14), whereas significant differences were noted in CT (p<0.001), ERFD (p<0.001), RSI (p<0.001), and CAF (p=0.01). In CMJ, significant positive correlations were identified between JH and RSI, PF, and CAF (RSI: r=0.44, p=0.036; PF: r=0.48, p=0.022; CAF: r=0.55, p=0.007). Moreover, CT exhibited a significant negative correlation with RSI, ERFD, and PRFD (RSI: r=-0.66, p=0.001; ERFD: r=-0.47, p=0.025; PRFD: r=-0.44, p=0.034) and a significant positive correlation with AT (p>0.05). During DJ, JH was significantly positively correlated with CAF and RSI (RSI: r=0.76, p<0.001; CAF: r=0.66, p<0.001), whereas CT was significantly negatively correlated with RSI (r=-0.48, p=0.021). Notably, increasing the drop height altered these relationships. **Conclusion.** These findings collectively reveal that CMJ and DJ differ in influencing factors, suggesting that athletes should tailor their training strategies according to the type of jump.

KEYWORDS: ***Plyometric Exercise, Jumping, Athletic Performance, Muscle Stretching Exercise.***

INTRODUCTION

Jump landing tasks are frequently employed as a non-specific tool to quantify the capabilities of athletes' lower extremity neuromuscular system, thereby assessing performance across various athletic endeavors (1-3) and potential risks for lower extremity injuries (4-6). Its utilization may be ascribed to jump-landing tasks being a foundational movement pattern prevalent across

*. Corresponding Author:
Ming Li, Ph.D.
E-mail: lming@jbnu.ac.kr
Sukwon Kim, Ph.D.
E-mail: rockwall@jbnu.ac.kr
♣. Maolin Dong and Youngsuk Kim share the first authorship.

multiple sports (7-9). For instance, a study focusing on NCAA Division I female volleyball teams reported that each player performed an average of 45 jump actions during two matches, with a maximum of 73 jumps (9). Another study indicated that basketball players execute an average of 46±12 jump landing tasks during a match (8). The results obtained from jump-landing tasks demonstrate satisfactory cross-disciplinary transferability, rendering jump-landing tasks a valuable evaluation tool.

As typical jump landing tasks, countermovement jump (CMJ) and drop jump (DJ) are extensively employed for assessing athletic performance (2, 7). Traditionally, jump height (JH) and ground contact time (CT) serve as essential parameters for measuring these movements. Meanwhile, complex metrics such as the reactive strength index (RSI) are used to reflect the capabilities of the stretch-shortening cycle (SSC) (2). At the same time, peak ground reaction force (PF), concentric phase average force (CAF), rate of force development (RFD), and vertical stiffness are generally employed to evaluate force output, explosiveness, movement economy, and risk of muscular injury (10-12). Additionally, amortization phase time (AT) is commonly employed to evaluate the energy transition efficiency from the eccentric phase to the concentric phase (13). While these diverse evaluation metrics offer comprehensive information and training guidance, their selection also introduces complexity. Hence, elucidating the interrelatedness among these various metrics is crucial to devising targeted training plans.

Although the relationship between RSI and RFD with JH has been extensively examined in prior CMJ studies, the results are conflicting. Compared to CMJ, research on DJ predominantly focuses on the influence of different drop heights on JH and RSI. However, less attention has been paid to the interrelations between variables in DJ. Given these inconsistencies and research gaps, the present study aimed to build on existing literature and investigate correlations between JH and CT and other assessment metrics during CMJ and DJ. Moreover, the impact of increasing the drop height by 30 cm on these correlations was examined. This study aimed to address current inconsistencies, fill knowledge gaps, and offer more precise references for assessing athletic performance and formulating goal-directed training strategies. The present study hypothesized that JH was positively correlated with RSI, PF, and CAF in CMJ and DJ, whereas CT was negatively correlated with RSI and EV and positively correlated with AT. Additionally, we presumed that elevating the drop height by 30 cm in drop height would enhance the correlations between JH, CT, and the remaining evaluation metrics.

MATERIALS AND METHODS

Participants. A priori power analysis was conducted using G*Power 3.1.9.7 software to determine the required sample size. Based on an alpha level of 0.05 and a beta level of 0.8, our calculation determined that a minimum of 21 participants was required. Initially, 26 participants were recruited. All participants were male university athletes from the same training team, with 5-8 years of badminton training experience (age = 22±2 years; height = 1.78±0.02 m; body mass = 70.43±2.43 kg; mean±SD). However, three participants eventually withdrew from the study due to participation in competitions, resulting in a final sample size of 23. These individuals maintained a training frequency of 3-4 times per week, each lasting 2-3 hours. Before the experiment, all participants were fully informed regarding the study objectives, experimental procedures, and potential risks and provided written informed consent. Comprehensive medical records were reviewed to exclude individuals with neuromuscular disorders and ensure that participants were suitable for the study. This study strictly adhered to the ethical guidelines of the Declaration of Helsinki and was approved by the Institutional Ethics Committee of the University (JBNU2022-01-004-002).

Design and Procedures. This study employed a cross-sectional design to examine the relationships between JH, CT, and other key performance parameters in CMJ and DJ activities. Additionally, the potential impact of a 30 cm increase in height on these relationships was further examined. All tests were scheduled during the pre-competition training phase to minimize the influence of external confounders. Prior to formal testing, multiple familiarization sessions were undertaken by all participants to attenuate learning effects (14). All testing procedures were completed within a single test day. Before performance assessments, detailed measurements of each participant's height and weight were recorded. Subsequently, participants completed a 15-minute warm-up session, adhering to the RAMP (Raise, Activate, Mobilize, Potentiate) principle (15). Following the warm-up phase, participants underwent a 5-minute rest period to decrease body temperature and restore oxygen consumption to baseline levels (16). Afterward, CMJ and DJ tests were conducted. To further adjust for potential confounders, participants were instructed to avoid high-intensity exercise and alcohol consumption 48 hours before testing, refrain from caffeine 8 hours before testing, and fast 2 hours before the assessment.

Measures. CMJ and DJ tests were performed on a force platform (Advanced Mechanical Technology, Inc., Watertown, MA, USA). Prior to the CMJ test, participants were instructed to stand with their feet parallel. Concerning the DJ test, the initial position was set on a 30 cm high plastic platform. This height was selected based on observations from previous research indicating that a 30 cm drop height could effectively enhance joint stability and mitigate the risk of injury through co-contraction (17). In each type of jump test (CMJ and DJ), participants initially completed 1-2 maximal effort attempts, followed by three valid official attempts. Rest periods between CMJ repetitions were set at 1 minute, while those between DJ repetitions were 1.5 minutes apart. A 3-minute recovery period was allocated between the two types of tests to limit fatigue accumulation (18). Throughout the tests, participants were directed to place their hands on their hips to eliminate the potential influence of arm swings on jumping performance (19). All jumping actions were continuously executed without mid-jump pauses, and participants were allowed to choose their countermovement depth. This design was based on prior research that suggested self-selected depth enables a more accurate assessment of jump performance than fixed depths (20). Participants were instructed to exert maximal effort to achieve the highest jump height while maintaining an upright posture for all jump tests. If the research team or athlete deemed any jump did not meet the criteria for maximal effort, that particular attempt was invalidated and repeated.

Data collection. To ensure highly accurate data acquisition, the OptiTrack optical motion capture system (Natural Point, Inc., Corvallis, OR, USA), equipped with 13 Prime 17W infrared cameras for recording the test movements, was employed in this study. The sampling rate was set at 100Hz. A total of 20 reflective markers measuring 14 mm each were placed on the anatomical landmarks of the lower extremities. Concurrently, the OR6-6-2000 force platform (Advanced Mechanical Technology, Inc., Watertown, MA, USA) was utilized at 1000Hz for measuring various force metrics. Motive 2.2.0 software (OptiTrack, Natural Point, Inc., Corvallis, OR, USA) was used for data integration to synchronize the two systems.

Data Processing. Ground reaction forces and center of mass (COM) displacement data were extracted using Visual3D Setup x64 v2022.9.1 software (C-Motion, Inc., Germantown, MD, USA). The initiation and termination of movements were determined based on the flight phase force's five standard deviations and a 20N force threshold (21). The force-time curve underwent a 17 Hz bidirectional fourth-order Butterworth low-pass filter, while the displacement-time curve was smoothed with a 6 Hz filter of the same type (21, 22). The reliability of the three individually collected sets of force-time data was assessed to ensure data reliability. Two sets with the highest intraclass correlation coefficients exceeding 0.8 were selected for subsequent analysis (23).

Based on the COM displacement-time data, the jumping action was categorized into three distinct phases: 1) Eccentric Phase: extending from the instant of minimum ground reaction forces to the moment when the COM reaches its lowest position; 2) Concentric Phase: from when the COM is at its lowest position to take-off; 3) Amortization Phase: the duration where the COM maintains its lowest position (24). The following parameters were extracted from the force-time data: minimum and maximum ground reaction forces during the eccentric phase (MinF and MaxF), time taken from MinF to MaxF (EMT), and total time of this phase (ET), AT, CT, CAF, PF, and the time to reach PF (PFT).

Additionally, based on the displacement-time data, standing phase COM height (SH), lowest COM point height (MH), and COM height corresponding to PF (PFH), as well as the maximum COM height reached during the jump (PH), were determined. Using these parameters, the following metrics were calculated: Eccentric Phase rate of force development (ERFD = (MaxF-MinF)/EMT), peak rate of force development (PRFD = PF/PFT), jump height (JH = PH-SH), vertical stiffness (PF/(SH-PFH)), reactive strength index (RSI = JH/CT), and average velocity during the Eccentric Phase (EV = (SH-MH)/ET). The mean of the metrics calculated from the two tests was used for analysis. All relevant parameter calculations were performed in the Microsoft Excel 2019 version (Microsoft Corp., Redmond, WA, USA).

Statistical Analysis. Statistical analysis was conducted using R software, version 4.3.1 (Foundation for Statistical Computing, Vienna, Austria). All variables were expressed as Mean±SD. Prior to statistical analysis, the normality of all datasets was confirmed via the Shapiro-Wilk test. The paired-sample T-test was used to compare variables JH, CT, ERFD, RSI, and CAF between CMJ and DJ. Additionally, Cohen's d-effect size was employed to quantify the magnitude of these differences (25). Spearman rank correlation analysis was employed to examine correlations between vertical stiffness and other variables, while Pearson product-moment correlation was used to identify correlations among other variables. Throughout the correlation analyses, Hopkins' interpretive guidelines were adopted to assess the strength of the correlation coefficients: trivial (0-0.1), small (0.1-0.3), moderate (0.3-0.5), large (0.5-0.7), or very large (0.7-0.9) (7). The threshold for statistical significance was set at r=0.25, with a required p-value of less than 0.05.

RESULTS

Tables 1 and 2 present the mean and standard deviation of performance metrics for CMJ and DJ. No significant difference was observed in JH between CMJ and DJ (p=0.143, d=0.32). However, significant differences were noted in CT, ERFD, RSI, and CAF (CT: p<0.001, d=2.63; ERFD: p<0.001, d=1.06; RSI: p<0.001, d=1.91; CAF: p=0.011, d=0.58) (see Table 1).

Table 1. Differences in variables related to CMJ and DJ (n=23)

	Mean±SD		95% Confidence limits	
Variable	**CMJ**	**DJ**	**P**	**d**
JH (m)	0.48±0.61	0.48±0.05	0.14	0.32
CT (s)	0.88±0.12	0.6±0.09	0.000*	2.63
ERFD (KN/s)	4.32±1.31	11±5.6	0.000*	1.06
RSI (m/s)	0.55±0.83	0.82±0.19	0.000*	1.91
CAF(KN)	1.27±0.11	1.3±0.1	0.01*	0.58

JH: Jump Height; CT: Ground Contact Time; ERFD: Eccentric Phase Rate of Force Development; RSI: Reactive Strength Index; CAF: Average Force during the Concentric Phase.

*: Significant at p<0.05; p: p-value; d: Effect Size.

Table 2. Mean and Standard Deviation of Variables (n=23)

Variable	CMJ	DJ
EV (m/s)	0.66±0.14	1.28±0.27
AT (ms)	16±8.8	15.4±7.69
PRFD (KN/S)	1.49±0.43	8.29±4.18
PF (N)	1.61±0.17	1.68±0.22
Vertical stiffness (KN/m)	24.93±26.85	27.37±50.42

EV: Average Velocity; AT: Amortization Time; PRFD: Peak Rate of Force Development; PF: Peak Ground Reaction Force.

Additionally, during CMJ, significant positive correlations were detected between JH and RSI, PF, and CAF (RSI: r=0.44, p=0.036; PF: r=0.48, p=0.022; CAF: r=0.55, p=0.007). Importantly, CT was significantly and negatively correlated with RSI, ERFD, and PRFD (RSI: r=-0.66, p=0.001; ERFD: r=-0.47, p=0.025; PRFD: r=-0.44, p=0.034) and positively correlated with AT (r=0.48, p=0.021) (see Table 3). Meanwhile, significant positive correlations were observed between JH, RSI, and CAF during DJ (RSI: r=0.76, p<0.001; CAF: r=0.66, p<0.001). Lastly, CT was significantly negatively correlated with RSI (r=-0.84, p<0.001) (see Table 4).

Table 3. Interrelationships Among Variables in CMJ

	JH	CT	PRFD	vertical stiffness	RSI	PF	AT	EV	ERFD	CAF
JH	1									
CT	0.35	1								
PRFD	0.17	-0.44*	1							
vertical stiffness	-0.32	-0.08	-0.54†	1						
RSI	0.44*	-0.66†	0.56†	-0.26	1					
PF	0.48*	0.2	0.61†	-0.27	0.18	1				
AT	-0.07	0.48*	-0.39	0.25	-0.46*	-0.02	1			
EV	-0.16	-0.28	0.39	-0.52*	0.11	0.01	-0.45*	1		
ERFD	0.16	-0.47*	0.85†	-0.45*	0.51*	0.59†	-0.45*	0.4	1	
CAF	0.55†	0.18	0.31	-0.23	0.2	0.81†	-0.02	-0.17	0.51*	1

JH: Jump Height; CT: Ground Contact Time; PRFD: Peak Rate of Force Development; RSI: Reactive Strength Index; PF: Peak Ground Reaction Force; AT: Amortization Time; EV: Average Velocity; ERFD: Eccentric Phase Rate of Force Development; CAF: Average Force during the Concentric Phase.

*: Significant at $p < 0.05$.

†: Significant at $p < 0.01$.

Table 4. Interrelationships Among Variables in DJ

	JH	CT	PRFD	vertical stiffness	RSI	PF	AT	EV	ERFD	CAF
JH	1									
CT	-0.29	1								
PRFD	0.18	-0.03	1							
vertical stiffness	0.17	-0.17	0.27	1						
RSI	0.76†	-0.84†	0.1	0.13	1					
PF	0.39	-0.19	0.08	-0.27	0.36	1				
AT	-0.34	0.11	-0.05	0.37	-0.24	-0.33	1			
EV	0.21	-0.17	-0.32	-0.71†	0.24	0.51*	-0.26	1		
ERFD	0.04	0.00	0.81†	0.57†	0.03	0.1	0.07	-0.56	1	
CAF	0.66†	-0.38	0.05	-0.3	0.66*	0.82†	-0.24	0.37	0.11	1

JH: Jump Height; CT: Ground Contact Time; PRFD: peak rate of force development; RSI: Reactive Strength Index; PF: peak ground reaction force; AT: Amortization time; EV: Average Velocity; ERFD: Eccentric Phase Rate of Force Development; CAF: Average Force during the Concentric Phase.

*: Significant at $p < 0.05$.

†: Significant at $p < 0.01$.

DISCUSSION

The primary findings of this study are as follows: 1) An increase in drop height by 30 cm did not significantly increase JH but notably shortened CT while also elevating RSI, ERFD, and CAF. 2) During CMJ, the highest correlation coefficient was identified between JH and CAF, followed by PF and RSI. CT showed the closest relationship with RSI, followed by AT, ERFD, and PRFD. In DJ, the strongest correlation with JH was observed with RSI, closely followed by CAF. CT was significantly correlated with RSI. 3) Adding 30 cm to the drop height altered variables related to JH and CT. Specifically, this modification strengthened correlations with RSI and CAF while diminishing those with other performance metrics.

Of note, a previous study compared different drop heights and their effects on jump performance to identify the impact of a 30 cm increase in drop height on JH, CT, RSI, ERFD, and CAF. The findings exposed that a 30 cm increase in drop height did not significantly alter JH but markedly reduced CT and increased RSI (26). These observations are consistent with our study observations. This outcome may be ascribed to biomechanical factors: compared to CMJ, the eccentric phase is shortened upon ground contact in DJ, reducing the time window for force generation. However, the force output during the concentric phase is enhanced. These biomechanical shifts may account for the comparable JH and lower CT upon adding 30 cm to the drop height.

Considering that RSI is calculated based on JH and CT, these factors conjointly led to a corresponding increase in RSI. This explanation aligns with the trend of these indices in our study. However, it is worthwhile to emphasize that previous research relied on flight time to calculate JH, the accuracy of which may be limited by the moments selected for take-off and landing.

In contrast, this study employed an optical motion capture system, providing higher measurement accuracy. Prior investigations primarily addressed ERFD and CAF in the context of CMJ. These studies generally focused on two aspects: 1) comparing ERFD and CAF among different populations (27); 2) exploring correlations between ERFD and CAF as independent variables and other performance parameters (28). Nevertheless, research on these parameters as dependent variables in comparative studies between CMJ and DJ is relatively sparse. This may be because past research emphasized overall performance without investigating differences in performance metrics across various phases in CMJ and DJ. Herein, ERFD and CAF were significantly elevated, possibly due to the body possessing initial momentum just before landing during DJ, which increased the speed and load of lower limb muscle contractions, not only improving ERFD but also potentially facilitating the storage of elastic potential energy and enhancing the stretch reflex (29), thereby elevating CAF during the concentric phase.

In terms of JH-related variables, previous research has yielded contradictory results. For instance, an earlier study discovered a relationship between JH and RSI but found no significant correlation with ground reaction forces at various phases (7). Another study identified a correlation between JH, PF, and PRFD (28). Our study results agree with prior findings regarding the correlation between PF, RSI, and JH but offer novel evidence divergent from the existing literature on PRFD. Such discrepancies may be attributed to the variance in the populations studied.

On the one hand, subjects in the first prior study were mainly soccer players, whereas those in the second were untrained in explosive movements and resistance exercises. On the other hand, our study involved systematically trained badminton athletes who excel in SSC activities (30). Regarding CT-associated variables, our findings were generally consistent with the observations of prior research. Specifically, CT was negatively correlated with RSI and ERFD and positively correlated with AT (7, 28, 31). However, one distinguishing factor is that previous studies either employed relatively short intra-group rest intervals (10-15 s) or did not adjust for arm movement.

Conversely, our study used longer intra- and inter-group rest intervals to mitigate fatigue effects (18) and explicitly adjusted for arm motion to eliminate data bias due to arm-swing techniques (19). The underlying mechanisms for these observations could be linked to the nature of JH and CT. In other words, the magnitude of JH is principally influenced by the applied force and its duration (i.e., impulse) (32), while that of CT is affected by the speed of the action. Therefore, our findings indicated a stronger correlation between JH and ground reaction forces, whereas CT was closely correlated with RSI and ERFD, reflecting SSC capability and explosiveness, respectively (2, 11).

Concerning the pronounced correlation between JH and CT with RSI and CAF as the drop height was extended by 30 cm, a possible explanation is that as the drop height attained 30cm, the contribution of SSC to jumping performance became increasingly significant (3), which in turn, amplified the correlation between JH and CT with RSI and CAF. This finding fills a gap in existing research, which chiefly focused on the effects of different drop heights and types of jumps on RSI (3) and the relationship between CAF and jumping performance in CMJ (33) while relatively overlooking correlations between these variables and jumping performance under varying conditions.

CONCLUSION

This study found that ground reaction force and SSC capacity are crucial in influencing JH, while SSC capacity and explosiveness significantly impact CT. Additionally, as the drop height increased to 30 cm, the importance of SSC capacity on jump performance incrementally increased.

The current study has some limitations that warrant further exploration and acknowledgment. Our findings' generalizability is constrained because the sample is limited to professional badminton athletes. This implied that our results may not apply to other types of athletes or the general population. Future research could consider including a more diverse array of athletes or participants of various ages and genders to enhance the universality and comparability of the findings. Secondly, our study employed a cross-sectional design and mainly used correlational analysis methods. While this framework aids in exploring relationships between variables, it does not establish explicit causal relationships. Therefore, despite our findings filling specific gaps in the existing literature, further longitudinal studies are necessitated to validate and support these preliminary results.

APPLICABLE REMARKS

- For athletes primarily engaged in countermovement actions at ground level, if the goal is to improve JH, the focus should be more on strength training, followed by SSC capacity.
- If the priority is enhancing movement speed, SSC capacity should be prioritized first, followed by explosiveness.

AUTHORS' CONTRIBUTIONS

Study concept and design: Maolin Dong, Youngsuk Kim, Ming Li, Sukwon Kim. Acquisition of data: Maolin Dong, Yanjia Xu, Bin Zhu, Ming Li. Analysis and interpretation of data: Maolin Dong, Youngsuk Kim, Yanjia Xu, Bin Zhu, Sukwon Kim. Drafting the manuscript: Maolin Dong, Youngsuk Kim, Ming Li. Critical revision of the manuscript for important intellectual content: Ming Li, Sukwon Kim. Statistical analysis: Maolin Dong, Youngsuk Kim, Sukwon Kim. Administrative, technical, and material support: Ming Li, Sukwon Kim. Study supervision: Youngsuk Kim, Sukwon Kim.

CONFLICT OF INTEREST

The authors affirm that they have no relationships or financial interests that might appear to conflict with the work described in this paper.

FINANCIAL DISCLOSURE

The authors affirm that they have no relationships or financial interests that might appear to conflict with the work described in this paper.

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ETHICAL CONSIDERATION

This article does not contain any studies involving animals performed by any of the authors. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. This study was reviewed and approved by the Ethics Committee of the Jeonbuk National University (protocol code: JBNU2022-04-008-002; approval date: 26 May 2022).

ROLE OF THE SPONSOR

No sponsor.

ARTIFICIAL INTELLIGENCE (AI) USE

No AI was used to prepare the manuscript.

REFERENCES

1. Djurić D, Pleša J, Van Hooren B, Kozinc Ž, Šarabon N. The relationship between elastography-based muscle properties and vertical jump performance, countermovement utilization ratio, and rate of force development. Eur J Appl Physiol. 2023;123:1789–1800. [doi:10.1007/s00421-023-05191-7] [PMid:37043001]
2. Jarvis P, Turner A, Read P, Bishop C. Reactive Strength Index and its Associations with Measures of Physical and Sports Performance: A Systematic Review with Meta-Analysis. Sports Med. 2022;52:301–330. [doi:10.1007/s40279-021-01566-y] [PMid:34606061]
3. Prieske O, Chaabene H, Puta C, Behm DG, Büsch D, Granacher U. Effects of Drop Height on Jump Performance in Male and Female Elite Adolescent Handball Players. Int J Sport Physiol. 2019;14:674–680. [doi:10.1123/ijspp.2018-0482] [PMid:30427227]
4. Harato K, Morishige Y, Kobayashi S, Niki Y, Nagura T. Biomechanical features of drop vertical jump are different among various sporting activities. BMC Musculoskelet Disord. 2022;23:331. [doi:10.1186/s12891-022-05290-0] [PMid:35395841]

5. Malaver JR, Cubides JR, Argothy R, Cohen DD. Risk Factors Associated With Medial Tibial Stress Syndrome In Military Cadets During Basic Training. Med Sci Sports Exercise. 2019;51:268–268. [doi:10.1249/01.mss.0000561309.34972.93]
6. Read PJ, Oliver JL, De Ste Croix MBA, Myer GD, Lloyd RS. A prospective investigation to evaluate risk factors for lower extremity injury risk in male youth soccer players. Scand J Med Sci Spor. 2018;28:1244–1251. [doi:10.1111/sms.13013] [PMid:29130575]
7. Barker LA, Harry JR, Mercer JA. Relationships Between Countermovement Jump Ground Reaction Forces and Jump Height, Reactive Strength Index, and Jump Time. J Strength Cond Res. 2018;32:248–254. [doi:10.1519/JSC.0000000000002160] [PMid:28746248]
8. Ziv G, Lidor R. Vertical jump in female and male basketball players—A review of observational and experimental studies. J Sci Med Sport. 2010;13:332–339. [doi:10.1016/j.jsams.2009.02.009] [PMid:19443269]
9. Ziv G, Lidor R. Vertical jump in female and male volleyball players: a review of observational and experimental studies: Vertical jump in volleyball players. Scand J Med Sci Spor. 2010;20:556–567. [doi:10.1111/j.1600-0838.2009.01083.x] [PMid:20459471]
10. Ericksen HM, Gribble PA, Pfile KR, Pietrosimone BG. Different Modes of Feedback and Peak Vertical Ground Reaction Force During Jump Landing: A Systematic Review. J Athl Training. 2013;48:685–695. [doi:10.4085/1062-6050-48.3.02] [PMid:24067153]
11. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J. Rate of force development: physiological and methodological considerations. Eur J Appl Physiol. 2016;116:1091–1116. [doi:10.1007/s00421-016-3346-6] [PMid:26941023]
12. Pearson SJ, McMahon J. Lower limb mechanical properties: determining factors and implications for performance. Sports Med. 2012;42(11):929-40. [doi:10.1007/BF03262304] [PMid:23009192]
13. Ishikawa M, Komi PV. Effects of different dropping intensities on fascicle and tendinous tissue behavior during stretch-shortening cycle exercise. J Appl Physiol. 2004;96:848–852. [doi:10.1152/japplphysiol.00948.2003] [PMid:14594857]
14. Cadens Roca M, Planas-Anzano A, Peirau-Terés X, Bishop C, Romero-Rodríguez D, Madruga-Parera M. Relationship between Asymmetry Profiles and Jump Performance in Youth Female Handball Players. J Hum Kinet [Internet]. 2023 [cited 2023 Oct 5]. [doi:10.5114/jhk/163432] [PMid:37559760]
15. Myburgh GK, Pfeifer CE, Hecht CJ. Warm-ups for Youth Athletes: Making the First 15-Minutes Count. Strength Cond J. 2020;42:45–53. [doi:10.1519/SSC.0000000000000549]
16. Bishop D. Warm Up II: Performance Changes Following Active Warm Up and How to Structure the Warm Up. Sports Med. 2003;33:483–498. [doi:10.2165/00007256-200333070-00002] [PMid:12762825]
17. Di Giminiani R, Giovannelli A, Capuano L, Izzicupo P, Di Blasio A, Masedu F. Neuromuscular Strategies in Stretch–Shortening Exercises with Increasing Drop Heights: The Role of Muscle Coactivation in Leg Stiffness and Power Propulsion. IJERPH. 2020;17:8647. [doi:10.3390/ijerph17228647] [PMid:33233323]
18. Mackala K, Stodółka J, Siemienski A, Ćoh M. Biomechanical Analysis of Squat Jump and Countermovement Jump From Varying Starting Positions. J Strength Cond Res. 2013;27:2650–2661. [doi:10.1519/JSC.0b013e31828909ec] [PMid:23552341]
19. Gillen ZM, Shoemaker ME, McKay BD, Bohannon NA, Gibson SM, Cramer JT. Influences of the Stretch-Shortening Cycle and Arm Swing on Vertical Jump Performance in Children and Adolescents. J Strength Cond Res. 2022;36:1245–1256. [doi:10.1519/JSC.0000000000003647] [PMid:32483060]
20. Read PJ, Oliver JL, Myer GD, De Ste Croix MBA, Lloyd RS. The Effects of Maturation on Measures of Asymmetry During Neuromuscular Control Tests in Elite Male Youth Soccer Players. Pediatr Exerc Sci. 2018;30:168–175. [doi:10.1123/pes.2017-0081] [PMid:28787266]
21. Li M, Meng X, Guan L, Kim Y, Kim S. Comparing the effects of static stretching alone and in combination with post-activation performance enhancement on squat jump performance at different knee starting angles. J Sport Sci Med. 2023;22:769. [doi:10.52082/jssm.2023.769] [PMid:38045747]
22. Escamilla RF, Fleisig GS, Zheng N, Barrentine SW, Wilk KE, Andrews JR. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises: Medicine &amp Science in Sports &amp Exercise. 1998;30:556–569. [doi:10.1097/00005768-199804000-00014] [PMid:9565938]

23. Janicijevic DN, Knezevic OM, Mirkov DM, Pérez-Castilla A, Petrovic MR, García-Ramos A. Magnitude and reliability of mechanical outputs obtained during loaded squat jumps performed from different knee angles. Sports Biomechanics. 2021;20:925–937. [doi:10.1080/14763141.2019.1618390] [PMid:31232220]
24. Barker LA, Harry JR, Mercer JA. Relationships between countermovement jump ground reaction forces and jump height, reactive strength index, and jump time. Journal of Strength and Conditioning Research. 2018;32:248–254. [doi:10.1519/JSC.0000000000002160] [PMid:28746248]
25. Fritz CO, Morris PE, Richler JJ. Effect size estimates: Current use, calculations, and interpretation. J Exp Psychol Gen. 2012;141:2–18. [doi:10.1037/a0026092] [PMid:21823805]
26. Young WB, Pryor JF, Wilson GJ. Effect of Instructions on characteristics of Countermovement and Drop Jump Performance. The Journal of Strength & Conditioning Research. 1995;9:232. [doi:10.1519/00124278-199511000-00005]
27. Cormie P, McBride JM, McCaulley GO. Power-Time, Force-Time, and Velocity-Time Curve Analysis of the Countermovement Jump: Impact of Training. J Strength Cond Res. 2009;23:177–186. [doi:10.1519/JSC.0b013e3181889324] [PMid:19077740]
28. McLellan CP, Lovell DI, Gass GC. The Role of Rate of Force Development on Vertical Jump Performance. J Strength Cond Res. 2011;25:379–385. [doi:10.1519/JSC.0b013e3181be305c] [PMid:20093963]
29. Taube W, Leukel C, Lauber B, Gollhofer A. The drop height determines neuromuscular adaptations and changes in jump performance in stretch-shortening cycle training. Scand J Med Sci Spor. 2012;22:671–683. [doi:10.1111/j.1600-0838.2011.01293.x] [PMid:21457355]
30. Pion J, Segers V, Fransen J, Debuyck G, Deprez D, Haerens L, Vaeyens R, Philippaerts R, Lenoir M. Generic anthropometric and performance characteristics among elite adolescent boys in nine different sports. European Journal of Sport Science. 2015;15:357–366. [doi:10.1080/17461391.2014.944875] [PMid:25143133]
31. Healy R, Kenny IC, Harrison AJ. Reactive Strength Index: A Poor Indicator of Reactive Strength? Int J Sport Physiol. 2018;13:802–809. [doi:10.1123/ijspp.2017-0511] [PMid:29182434]
32. Ruddock AD, Winter EM. Jumping depends on impulse not power. J Sport Sci. 2016;34:584–585. [doi:10.1080/02640414.2015.1064157] [PMid:26256791]
33. Laffaye G, Wagner P. Eccentric rate of force development determines jumping performance. Comput Method Biomec. 2013;16:82–83. [doi:10.1080/10255842.2013.815839] [PMid:23923859]