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Biomechanical Determinants of the Reactive Strength Index During Drop Jumps

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Abstract

The Reactive Strength Index (RSI) is often used to quantify drop-jump (DJ) performance; however, not much is known about its biomechanical determinants. The purpose of this study was to investigate the correlations between the RSI and several biomechanical variables calculated from DJ performed with different initial drop heights. Twelve male NCAA Division I basketball players performed DJs from drop heights of 30, 45, and 60 cm. Force plates were used to calculate DJ performance parameters (ie, DJ height, contact time, and RSI) and DJ biomechanical variables (ie, vertical stiffness and eccentric/concentric energetics). Regression analyses were used to assess the correlations between variables at each drop height, and ANOVAs were used to assess the differences of all variables across drop heights. Follow-up analyses used 2 neural networks to determine if DJ performance and biomechanical data could accurately classify DJ trials by drop-height condition. Vertical-stiffness values were significantly correlated with RSI at each height but did not change across drop heights. Surprisingly, the RSI and other DJ parameters also did not vary across drop height, which resulted in the inability of these variables to accurately classify DJ trials. Given that vertical stiffness did not change across drop height and was highly correlated with RSI at each height, the RSI appears to reflect biomechanical behavior related to vertical stiffness during DJ. However, the inability of the RSI to accurately classify drop-height condition questions the use of RSI profiles established from DJs from different heights.

Keywords: biomechanics; neuromuscular; neural network; training; monitoring

The Reactive Strength Index (RSI) is a measure often used to quantify dynamic lower-extremity performance during a drop jump (DJ).[1] [2] –[3] The RSI represents a highly reliable (ie, intraclass correlation coefficient >.90) and simple index of performance that is also easy to measure and interpret.[4] [5] –[6] The RSI is calculated as the quotient of DJ jump height and ground-contact time and reflects the ratio of how high an athlete jumps to how much time he or she spends on the ground.[1] It is common for DJ testing and RSI calculation to include conditions where the height of the drop is manipulated in order to establish an RSI profile, which can purportedly be used to investigate the effects of training and differences in skill or strength levels.[1] ,[3] Based on its inherent reliability, simplicity, and utility it has been suggested that the RSI is ideal for assessing cross-sectional differences and monitoring longitudinal changes in maximal dynamic lower-extremity performance.

Although the RSI provides simple insight into dynamic lower-extremity performance during a DJ, not much is known about its biomechanical determinants. Beyond the variables of jump height and ground-contact time, both of which are used to calculate RSI, no studies have investigated other biomechanical variables associated with the RSI. This lack of knowledge, however, presents a gap that may inhibit the optimal use of the RSI as a monitoring tool in the applied strength and conditioning setting, because practitioners cannot be confident of the characteristics that RSI actually measures. In this light, the benefit of being easily calculated from simple jump systems also represents a trade-off because such systems do not provide the in-depth information of force-plate analyses. It would therefore be of significant practical interest to determine the correlations between RSI- and force-plate-derived data to provide practitioners with better information about the biomechanical determinants of the RSI.

The instructions that are provided to athletes during DJs and RSI testing are typically to "jump as high and as fast as you can."[1] These instructions are provided to encourage athletes to maximize jump height and minimize ground-contact time, which in combination optimize RSI. Given that such instructions likely lead to large ground-reaction forces over small periods of time, it could be hypothesized that the RSI is associated with vertical stiffness.[7] ,[8] In addition, given that maximal DJ performance depends on optimal stretch-shortening-cycle function, it could also be hypothesized that the RSI is associated with the center-of-mass (COM) energetics.[9] Furthermore, since drop height is often manipulated during RSI testing and represents different stretch- and impact-load conditions during the DJ, one could further hypothesize that athletes adjust stiffness and energetic behavior to scale with such changes in height.[1] ,[3] In light of these hypotheses, the purpose of this study was to investigate correlations between RSI and biomechanical variables during a series of DJs performed from different heights, with the rationale that the knowledge of these correlations would provide useful information about the biomechanical determinants of the RSI. In particular, our analysis of variables focused on athletes' vertical stiffness and COM energetics during the eccentric and concentric phases of the DJ. A secondary purpose, which manifested as a follow-up analysis, was to determine if DJ performance parameters (ie, DJ height, contact time, and RSI) and DJ biomechanical data (ie, vertical stiffness and eccentric/concentric and work) could accurately classify DJ trials by drop height.

Methods

Participants

Twelve male NCAA Division I basketball players were recruited for this study (mean ± SD age 21.6 ± 1.8 y, height 1.93 ± 0.10 m, body mass 80.5 ± 10.5 kg). Before testing, all players were briefed on the scope of the study and read and signed an informed-consent document that was approved by the local university's institutional review board for human subjects testing.

Testing Protocol

All athletes were tested in the mornings before any skill or conditioning work. All were asked not to participate in heavy resistance training or intense conditioning sessions for 48 hours prior to testing. Before testing, each athlete performed a brief dynamic warm-up that included body-weight exercises (eg, squats, lunges) and a variety of submaximal- and maximal-effort countermovement jumps and squat jumps. Each participant then performed several submaximal-effort DJs, after which he performed 3 maximal-effort DJs from box heights of 30.5, 45.7, and 61 cm. To simplify, these heights are referred to as 30, 45, and 60 cm from here on. The explicit instructions were to "jump as high and as fast as you can." Approximately 30 seconds of rest were allowed between maximal-effort DJs. All athletes were familiar with the DJ through their regular strength and conditioning practices and were therefore provided with only minimal familiarization, which was primarily allocated so that each participant could get used to the layout of the force plates that were positioned approximately 15 cm in front of the box. DJ trials were excluded if the athlete either stepped down onto the force plate or jumped off of the box. All DJ trials were supervised by a certified strength and conditioning specialist.

Data Collection and Processing

For all DJs athletes landed on 2 AMTI force plates (Model OR6-6, Advanced Mechanical Technologies Inc, Watertown, MA, USA) that were mounted flush with the floor. Participants were positioned such that each foot landed fully on 1 of the 2 force plates. All processing occurred with custom-written MATLAB (The Mathworks Inc, Natick, MA, USA) programs. Kinetic data from the force plates were recorded at 1000 Hz and filtered with a fourth-order low-pass Butterworth filter and a cutoff frequency of 15 Hz, which was determined after an analysis of the residuals from several cutoff frequencies. The filtered vertical-ground-reaction-force (VGRF) data from both force plates were then summed into a single VGRF vector. The peak VGRF (F_{max}; N) and ground-contact time (t_c; s) were extracted for analysis (Figure 1[A]). The vertical-ground-reaction force−time curves were used to calculate the acceleration of the COM. The velocity of the COM during the contact phase of the DJ was calculated through numerical integration of the net vertical-acceleration data. The initial velocity of the COM was calculated from the flight times associated with the different drop heights.[10] The same procedure was repeated to calculate the COM position. The COM velocity was multiplied with the VGRF data to produce COM power, which in turn was used to identify eccentric (negative power) and concentric (positive power) movement phases (Figure 1[B]). Motion of the COM was also use to calculate the maximum vertical displacement (Δy; m) during the DJ. The power−time curves were numerically integrated to estimate eccentric (J_{Ecc}; $N \cdot m^{-1} \cdot kg^{-1}$) and concentric ($J_{Conc}$; $N \cdot m^{-1} \cdot kg^{-1}$) work. Vertical stiffness (k_{vert}; kN/m) was defined as the ratio of F_{max} to Δy.[11]

Classification of Neural Networks

Two separate feedforward neural networks were used to determine if DJ performance parameters (ie, DJ height, contact time, and RSI) and DJ biomechanical data (ie, vertical stiffness and eccentric/concentric work) could accurately classify DJ trials by drop height. Input data for both networks were randomly divided into training (70%), validation (15%), and testing samples (15%). The architecture of both networks consisted of 3 input layers, 10 hidden layers, and 1 output layer. In each case, the output layer reflected the drop height. The networks were trained with scaled conjugate gradient back-propagation, and network performance was assessed from the mean square error. Confusion matrices were then generated to assess the percentage of correctly and incorrectly classified DJ trials.

Statistical Analysis

Descriptive data are reported as mean ± SD. Preliminary analyses were performed for all data to ensure that requirements for parametric testing were met. Simple linear-regression analyses were used to test for correlations between RSI and biomechanical variables. Separate general linear analysis-of-variance (ANOVA) models were used to test for differences in dependent variables. Each ANOVA model consisted of a 3-way analysis to test for within-subject differences across the independent variable (ie, drop height). Within-subject differences were treated as repeated measures. Assumptions of the test statistic were verified with the Mauchly test of sphericity. Greenhouse-Geisser corrections were made when assumptions of sphericity were violated. Partial eta-squared (η^2) values were used to help interpret the magnitude of main effects. The criterion for statistical significance was set at an alpha level of.05. The reliability of all dependent variables for each drop height was assessed with intraclass correlation coefficients (Table [1]). All statistical analyses were performed in SPSS 24.0 (IBM Corp, Armonk, NY, USA).

Table 1 Intraclass Correlation Coefficients for All Dependent Variables at Each Drop Height

	30 cm	45 cm	60 cm
Height	.971	.853	.853
Ground-contact time	.940	.969	.978
Reactive Strength Index	.957	.986	.967
Peak vertical ground-reaction force	.975	.971	.974
Vertical displacement	.916	.872	.936
Eccentric work	.930	.958	.984
Concentric work	.945	.928	.956
Vertical stiffness	.985	.974	.987

Results

Main effects for drop height were observed for peak force, maximum vertical displacement, eccentric work, and concentric work (Table [2]). Post hoc testing indicated that peak force during the 60-cm DJ was greater than during the 30-cm DJ (P =.024) and that COM displacement during the 60-cm DJ was greater than during the 30-cm DJ (P =.002). Post hoc testing further indicated that eccentric work during the 60-cm DJ was greater than during the 45-cm DJ (P =.001) and 30-cm DJ (P =.001). In addition, eccentric work was greater during the 45-cm DJ than during the 30-cm DJ (P =.001). Conversely, post hoc testing indicated that concentric work during the 30-cm DJ was great than during the 45-cm DJ (P =.003) and the 60-cm DJ (P =.013).

Table 2 Performance Parameters and Biomechanical Variables During Drop Jumps Performed From 30-, 45-, and 60-cm Heights, Mean ± SD

	30 cm	45 cm	60 cm	P	η^2
Height (m)	0.489 ± 0.086	0.486 ± 0.073	0.495 ± 0.064	.499	.083
t_c (s)	0.330 ± 0.079	0.315 ± 0.083	0.322 ± 0.095	.339	.127
RSI (m/s)	1.57 ± 0.43	1.63 ± 0.43	1.64 ± 0.42	.367	.118
F_{max} (N)	3318 ± 678	3602 ± 821	3650 ± 842	.008	.455
Δy (m)	−0.233 ± 0.073	−0.260 ± 0.070	−0.303 ± 0.082	.001	.713
J_{Ecc} ($N \cdot m^{-1} \cdot kg^{-1}$)	−5.27 ± 0.74	−7.02 ± 0.70	−8.93 ± 0.83	.001	.986
J_{Conc} ($N \cdot m^{-1} \cdot kg^{-1}$)	7.14 ± 1.09	6.51 ± 1.32	6.05 ± 1.50	.003*	.643
k_{vert} (kN/m)	21.2 ± 12.3	19.9 ± 8.9	17.4 ± 7.2	.200	.195

Note: P values for significant main effects are presented in bold. *Greenhouse-Geiser correction.

Several of the correlations between RSI and biomechanical variables were significant (Table [3]). The RSI was correlated with vertical stiffness during the eccentric and concentric phases at all drop heights. The RSI was also significantly correlated with the amount of negative mechanical work during the DJ from all 3 drop heights. Positive mechanical work, however, was correlated with the RSI only at the 60-cm drop height.

Table 3 Correlation Coefficients Between RSI and Biomechanical Variables During Drop Jumps Performed From 30-, 45-, and 60-cm Heights

	30 cm	**45 cm**	**60 cm**
J_{Ecc}	.514**	.756***	.821***
J_{Conc}	−.037	−.070	−.389*
k_{vert}	.537**	.676***	.754***

*P <.05; **P <.01; ***P <.001.

The neural network with DJ performance parameters as input classified only 33.3% of all DJ trials correctly (Figure 2A). The respective percentage errors for training, validation, and testing were 63%, 75%, and 87%, respectively. In contrast, the neural network with DJ biomechanical data as input classified 96.3% of all DJ trials correctly (Figure 2B), and the respective errors for training, validation, and testing were 0%, 0%, and 25%, respectively.

Discussion

The primary purpose of this study was to investigate correlations between the RSI and other biomechanical variables during DJ from different drop heights. The major finding of this study was that values for vertical stiffness during DJ were consistently correlated with RSI across all drop heights. Furthermore, values of vertical stiffness did not change across drop heights. In combination, these results suggest that the RSI reflects biomechanical behavior associated with the vertical stiffness of the body's musculoskeletal system during DJ. The reason that vertical stiffness remained constant was likely that both peak ground-reaction forces and COM displacements increased concomitantly with drop height. An unexpected finding was that RSI did not change across drop height, which may be partially explained by the decrease in concentric work at greater drop heights. In contrast, greater drop heights were associated with more eccentric work, which likely reflect the differences in initial conditions. Finally, follow-up data analyses indicated that DJ biomechanical variables classified drop height more accurately than DJ performance parameters, which may question the practical utility of drop-height-based RSI profiles.

Vertical stiffness during DJ was significantly correlated to RSI at each of the 3 drop heights. The direction of all correlations was positive, which indicated that greater RSI values were associated with greater stiffness regardless of DJ phase. The strength of the correlation between RSI and vertical stiffness was greater at 45- and 60-cm heights than at the 30-cm height. That said, the actual values of vertical stiffness during the DJ did not differ across drop heights. Given that the peak ground-reaction forces and COM displacements during the DJ both increased concomitantly with drop height, this finding may not be too surprising since vertical stiffness is calculated from both variables. Similarly, Ferris et al reported that people run and hop with the same overall vertical stiffness, even across surfaces with different compliance levels.[12] ,[13] They suggested that, regardless of environmental condition, people maintain the same vertical stiffness in order to keep movement mechanics (eg, hopping frequency) constant. The similarity in stiffness values observed across drop heights may thus point to an attempt by the athletes to control and maintain constant jump mechanics in the face of greater impact forces, because DJ contact time and height also did not differ. Since the RSI was highly correlated with vertical stiffness at each drop height and did not change across heights, it appears to be closely linked to the vertical stiffness of the body's musculoskeletal system during DJ.

In regard to COM energetics, the results indicated that only the amount of mechanical work that was performed during the eccentric phase correlated with the RSI. The direction of all correlations between RSI and eccentric work was positive, and the magnitude of the associated correlation coefficients increased progressively from the 30-cm to the 60-cm drop height.

Given that eccentric work values are negative, the positive correlations thus indicate that greater RSI values are associated with smaller magnitudes of mechanical work performed during the eccentric phase of the DJ. To what extent the RSI reflects eccentric-phase energetics during the DJ is, however, less clear because the results also showed that an increase in drop height led to an increase in eccentric-phase work, which is likely due to the greater peak ground-reaction forces and COM displacements that were observed during the impact phase of DJ from greater drop heights. Furthermore, the results showed that an increase in drop height was associated with a decrease in concentric-phase work. Other authors have suggested that the ratio between concentric and eccentric work provides insight into the function and efficiency of the stretch-shortening cycle during jumping exercises.[14] The observed changes in COM energetics during the DJ in the current study may therefore indicate a decrease in muscle-tendon-unit efficiency and suggest that DJ performance and RSI are limited by stretch-shortening-cycle function.

The results showed that parameters of DJ performance (ie, RSI, DJ height, and contact time) did not change across drop heights. The lack of change in DJ performance parameters agrees with findings from other studies, which indicate that DJ starting height does not correlate well to DJ performance.[15] ,[16] More specifically, Walsh et al suggested that contact time has a greater effect on DJ performance parameters than drop height.[16] This implication may be especially important if technical instructions are not controlled and athletes perform DJ under inconsistent conditions.[17] Given that participants in the current study were provided with consistent instructions (ie, "Jump as high and as fast as you can") it may thus not be a surprise that contact time did not change.

In the absence of drop-height-dependent changes in DJ performance parameters it became of interest to pursue a follow-up analysis to determine how accurately the DJ performance parameters and DJ biomechanical data could classify individual DJ trials by initial conditions. To this end, 2 neural networks were trained to determine how accurately DJ trials could be classified by drop heights with either DJ performance parameters or DJ biomechanical data as inputs. The results of the classification analysis indicated that with DJ height, contact time, and RSI as inputs, the neural network classified the drop height of only approximately 33% of all DJ trials correctly. Given that DJ performance parameters did not change across drop height, the poor performance of this classification network was not too surprising. In contrast, the neural network with the DJ biomechanical data classified approximately 96% of all DJ trials correctly. The reason that this discrepancy should be of interest to coaches and sport scientists is that DJ testing across a spectrum of drop heights is used to identify a DJ profile with an ostensible optimal drop height based on either DJ height, contact time, or RSI. However, the collective results from the current study suggest that the 3 DJ performance parameters neither vary across nor accurately classify DJ trials by drop heights. While general plyometric training can increase the RSI,[18] no longitudinal studies have examined the effectiveness of targeted and RSI-specific training programs on DJ performance. In the absence of such training studies, the current results thus question the utility of RSI-based DJ profiles to guide the program-design process in the strength and conditioning setting. On the other hand, the current results suggest that the use of a single drop height could be sufficient to calculate the RSI profile, which would simplify DJ testing for practitioners.

The results from this study should be interpreted in light of a few limitations. First, the sample of athletes in this study consisted entirely of male NCAA Division I basketball players, which may limit the generalizability of the results to that population and sport. Another limitation is that we did not test squat-jump performance and did not calculate the difference in net concentric work between the squat jump and the DJ. The ratio of net concentric work to eccentric work is often used to provide insight into stretch-shortening-cycle function and muscle-tendon-unit efficiency.[9] ,[14] However, given the within-subject statistical design of the current study, the lack of squat-jump data should not influence the inferences related to the decreases in concentric work during the DJ that were observed from the greater drop heights or any proposed changes in stretch-shortening-cycle function. Finally, the contact times for all DJ in the current study (∼330 ms) were slightly longer than the typical 250-millisecond value typically associated with fast stretch-shortening-cycle and high-load plyometric exercises.[3] It is likely that the reason for this discrepancy was that athletes in the current study were allowed to use their arms during the execution of the DJ technique. While the execution of the DJ with arm swing likely lengthened the contact time compared to the hands-akimbo technique, the former technique was chosen to allow for a more natural and familiar motion for basketball players.

Practical Applications

There are 2 primary and immediate practical applications of the results from the current study. First, the results suggest that the RSI correlates well with vertical stiffness during a DJ, regardless of drop height. Given that practitioners often use DJ to assess and monitor lower-body performance, it would be beneficial for them to know that the RSI provides information about the stiffness of the lower extremities. The RSI could then be easily used as a surrogate of musculoskeletal stiffness in order to track performance characteristics and/or injury potential. Second, the results suggest that DJ performance parameters (ie, RSI, jump height, contact time) do not accurately differentiate individual DJ by drop height. This limitation brings into question whether it is necessary for practitioners to test DJ from multiple drop heights in order to establish an RSI profile. Collectively, these 2 results suggest that practitioners could use the RSI from only 1 drop height to gain insight into the stiffness behavior of the musculoskeletal system during DJ.

Conclusions

The RSI is highly correlated with vertical stiffness across a range of drop heights. Furthermore, vertical stiffness did not differ across drop height. The RSI therefore appears to reflect lower-extremity stiffness during DJ. However, the inability of RSI, DJ height, and contact time to accurately classify DJ trials by initial condition brings into question the utility of these parameters to establish drop-height-based RSI profiles.

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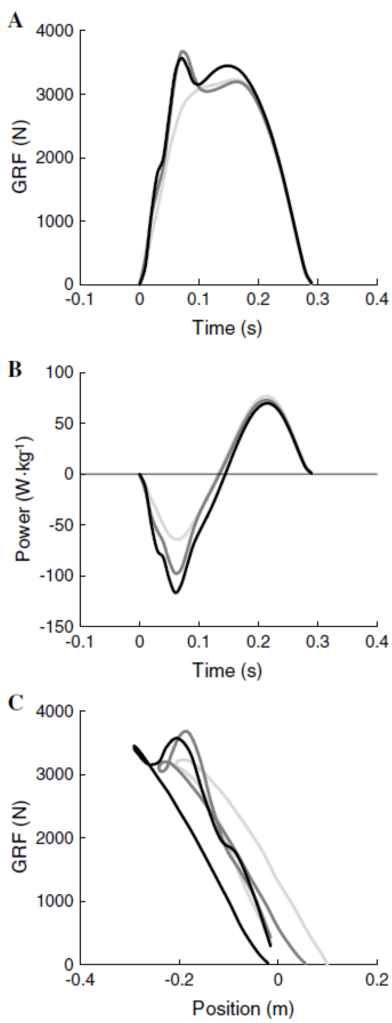
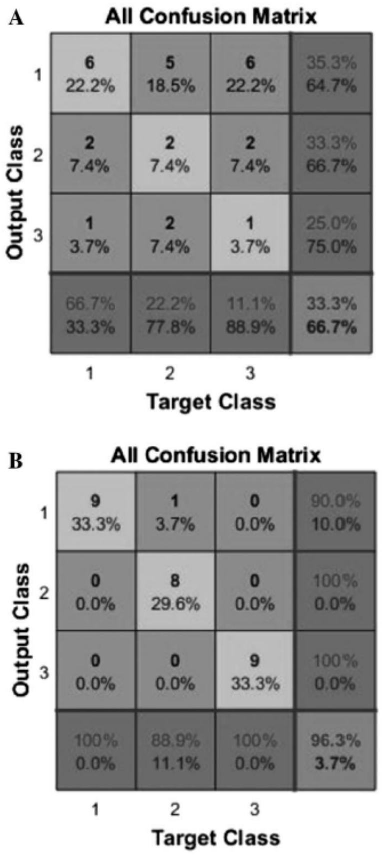


Graph: Figure 1 —Three-trial ensemble average of biomechanical data during the stance phase of drop jumps from 30-cm (light gray line), 45-cm (dark gray line), and 60-cm (black line) drop heights for 1 representative athlete. (A) Vertical ground reaction forces (GRF) versus time. (B) Center-of-mass system power versus time. (C) Vertical GRF) versus center-of-mass system position.



Graph: Figure 2 —Confusion matrices for neural networks with A) DJ performance parameters (ie, DJ height, contact time, and RSI) and B) DJ biomechanical data (ie, eccentric/concentric stiffness and work) as input. Class 1, 2, and 3 refer to drop heights 30 cm, 45 cm, and 60 cm, respectively. NOTE: Target and output refer to input and predicted (ie, classified) data, respectively.