Momentum-Based Load Prescriptions: Applications to Jump Squat Training

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Running Title: Prescribing Training Loads with Momentum

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Abstract

Velocity-based training is often applied to ballistic exercises, like the barbell jump squat, to improve vertical jump performance. However, determining the ideal training load based on velocity data remains difficult, as load prescriptions tend to be limited to subjective velocity loss thresholds, velocity ranges, or both. Using data from jump squats performed with 0%, 15%, 30%, 45%, and 60% of the 1-repetition maximum squat, we explored subjective and objective methods to determine the ideal training load. Specifically, we explored takeoff velocity and a related metric only recently discussed in the literature, system momentum (i.e., takeoff velocity multiplied by the mass of the athlete-load system). At the group level, an ideal training load could not be revealed objectively using takeoff velocity. With individual participants, the process remained challenging using takeoff velocity. Conversely, an ideal training load could be revealed easily and objectively using system momentum at the group average and individual participant levels. System momentum at takeoff is well-suited to assist practitioners seeking to identify appropriate training loads for jump squat training, and potentially other ballistic exercises. We suggest a pivot from velocity to system momentum when seeking to objectively establish training loads for the jump squat and related exercises.

Keywords: Jumping; momentum, resistance training; velocity-based training.

Introduction

The vertical jump is a primary measure of physical ability because it is strongly correlated with key physical attributes for many sports, such as speed, power production, strength, and agility (5, 17, 27). Because of the strong relationship between vertical jumping and athletic ability, resistance training prescriptions often use vertical jump performance as a primary outcome measure to determine the efficacy of interventions (2, 7, 13). The barbell-loaded jump squat (18, 21) is arguably one of the more effective exercises for improving jumping and related physical abilities (18, 21, 33). This is supported by evidence that loaded jump squat training can significantly increase lower body power production when an appropriate volume and intensity (e.g., 30% 1-repetition maximum squat for 6 sets of 6 repetitions 2 x per week for 8-weeks) is used (13). In addition, jump squat training with an appropriate volume and intensity can be equally as effective as weightlifting derivatives (e.g., hang pull) for improving lower body power production (28). Further, the jump squat is relatively simple in that it requires less experience from athletes and coaches to effectively perform and teach, respectively, when compared to weightlifting exercises and their associated derivatives (28). Therefore, the jump squat exercise is broadly applicable in many training environments.

The underlying mechanisms explaining how jump squat training improves vertical jump performance is multi-factorial, though movement velocity during the upward or concentric phase (10) is thought to be one important factor (16). When compared to squatting, the absence of voluntary deceleration during the concentric phase (i.e., need to stop motion) of jumping results in high reliability of velocity measures (29). This is because the objective of vertical jump movements is to move vertically with as much velocity as possible and takeoff velocity is the kinematic determinant of jump height (9). The load-velocity relationship (14) dictates that external loading will decrease the movement velocity at which an athlete can move during jump squat exercise. Still, the effectiveness of jump squat training with light relative loads for enhancing jump ability suggests decreasing takeoff velocity during training can provide an adequate stimulus for jumping-specific neuromuscular adaptations. This point is supported by related research in which different velocity loss thresholds (e.g., 10% or 20%) during power-oriented resistance training were effective at stimulating increased jump height (29). Unfortunately, it can be challenging to identify ideal velocity-loss thresholds for jump squat training, especially across disciplines and experience levels For example, there is a subject-specific relationship between velocity and the percentage of maximum strength (35), particularly for the light relative loads (30). As lighter loads are typically prescribed during jump squat training, it is unlikely that blanket percentages applied to all athletes is appropriate for a given athlete or exercise. This problem remains when using suggested velocity ranges (19) for specific training goals (e.g., speed-strength), as it is unlikely that such ranges are applicable for all exercises prescribed to multiple athletes training for the same goal (e.g., improved jump height following jump squat training).

One less-emphasized variable that has only become a focus in recent jump-training research is that of ‘jump momentum’. Momentum is the product of an object’s mass and velocity (35), and the importance of monitoring momentum relative to jumping abilities, general sport success, and the relation between both jump- and sprint momentum (20, 22, 23) and force asymmetry (11) has been previously discussed. Redirecting the focus for jump-training load prescription from *velocity loss* to *maximizing momentum* can mitigate some challenges associated with establishing velocity-loss training targets for the exercise because system momentum (i.e., athlete plus load) displays a unimodal profile across loads, which is discussed later in detail alongside data. This is because a heavy system moving slowly can have more momentum than a light system moving fast, and the concept can be understood using heavy squats as an example. For example, consistently performing a heavy squat exercise in training should improve vertical jump performance (1) even though they are performed with very low velocities compared to the velocities associated with jumping (31). Documented enhancements in jump performance following jump squat training (13, 21) likely occurred because participants were generating greater momentum during training. Load prescriptions based on maximizing momentum could be more feasible in practice than velocity loss (26, 29) or suggested velocity ranges (19).

Therefore, the purpose of this technical report is to provide a brief, theoretical explanation for monitoring or prescribing ballistic exercise intensity according to an athlete’s system momentum, using data collected from 12 resistance trained males during jump squat exercise. Our goal was to demonstrate the relationship between the takeoff momenta developed during jump squat exercise of various loads to contextualize the method for practical application.

Summary of Data Collection Methods

The detailed protocol to collect the data used herein can be found in the study by Barker and colleagues (3). In short, we used a subset of data obtained from 12 resistance trained males (≥ 2 weekly training sessions for at least 1 year; with training including jumping and squatting variations) who provided informed written consent as approved by the Institutional Review Board at the site of data collection. The participants performed sets of 3 repetitions of jump squat exercise at incremental loads (0, 15, 30, 45, and 60% of estimated back squat 1-repetition maximum). The data only include jumps with a preferred countermovement depth, and the objective of each jump was to move as quickly as possible and jump as high as possible. Force platform data were collected to obtain the participants' system mass (participant body mass + load), center of mass velocity at takeoff (i.e., jump height), and total body momentum at takeoff (system mass multiplied by velocity at takeoff).

Understanding and Obtaining System Momentum

An athlete's momentum represents their quantity of motion, and the change of momentum is calculated as mass (m) multiplied by the change of velocity (Δv) during a movement (8). The change in momentum is equal to the athlete's applied impulse ($\Sigma F \Delta t$), which is calculated as their net force application (ΣF) multiplied by the duration of force application (Δt). This impulse-momentum relationship is derived from Newton's law of acceleration (Equation 1.1), and acceleration (a) is the change of velocity (Δv) divided by the change of time (Δt) as shown in the rearranged form of Equation 1.1 (Equation 1.2). By rearranging Equation 1.2 to isolate momentum ($m\Delta v$) the impulse-momentum relationship is revealed (Equation 1.3).

Eq. 1.1: $\Sigma F = ma$

Eq. 1.2: $\Sigma F = m(\Delta v/\Delta t)$

Eq. 1.3: $\Sigma F\Delta t = m\Delta v$

Impulse is often calculated from force platform data to obtain momentum and velocity and then determine jump performance, defined by jump height (15, 24, 32). Because force platforms might not be accessible in all training environments, any other technology (e.g., video, tether-based devices, accelerometers, etc.)

providing velocity during an exercise (e.g., barbell velocity) can be used as a surrogate to obtain these metrics. For environments with access to force platforms, velocity can be obtained from the ground reaction force data by first using Equation 1.1 above to calculate acceleration and then calculating the time-integral of the acceleration (4, 10, 12). Takeoff velocity should be used rather than peak velocity because velocity decreases immediately prior to takeoff and it therefore directly reflects the athlete's jump height and net impulse. Peak velocity can be a reasonable surrogate for takeoff velocity when necessary, but it will overestimate impulse, momentum, and jump height. System momentum is calculated as the product of the change of velocity (i.e., takeoff velocity minus 0) and the sum of the athlete's body mass and the load lifted (Equation 2).

Eq. 2: $m\Delta v_{system} = \Delta v(m_{athlete} + m_{load})$

Why Momentum Instead of Power?

The primary metric that could be mistakenly considered valuable when considering training loads for ballistic exercises is power. However, we argue that power should not be considered in this context because it is a blend of output and strategy due to it being the product for force (strategy) and velocity (output). Power is therefore a poor representation of an athlete's cumulative effort during a ballistic exercise because the power output at the time when performance is determined (takeoff) is near zero, as force cannot be applied when the lower body joints are extended, while the coinciding amount of velocity is what determines the exercise's performance output. While it is possible to use peak or mean power during the exercise to circumvent the return of zero power at takeoff, that process is distanced from the actual output of a ballistic exercise. However, when system momentum at takeoff is used, the cumulative effort (applied impulse) and that effort's effect (change of momentum) are obtained. From a training perspective, a larger system momentum at takeoff during one load versus another load would indicate a more stimulating demand was placed on the athlete, resulting in greater effort regardless of whether they applied larger average forces or moved at a slower velocity.

Practical Applications: Momentum versus Velocity for Ballistic Load Prescriptions

As previously mentioned, the load-velocity relationship dictates that velocity will decrease during loaded jumps as a result of greater inertia from the added load, and this is supported by our data (Figure 1; Table 1). Current best practices include two methods for velocity-based load prescription. One practice incorporates velocity loss thresholds, such as a 10% or 20% decrease (26, 29), and the heaviest load that can be lifted within those thresholds should be prescribed. The other practice incorporates suggested velocity ranges for specific training goals (19), such as "speed-strength" for jump squats or similar exercises (25), where 25% to 45% of the 1-repetition maximum should be lifted within a 0.75 m/s to 1.0 m/s velocity range (19). We recommend determining a velocity loss threshold based on the percent change from unloaded to each load relative to the unloaded coefficient of variation during unloaded jump squats (6) to try and ensure that load prescriptions are objectively established. In other words, the ideal training load would be determined as the heaviest load associated with a decrease of velocity that is not greater than the typical amount of variation. Using that approach, we observed that incrementally increasing the load up to 60% led to decreases of the takeoff velocity relative to unloaded jumps, as to be expected. However, the problem for practitioners relates to how it can be possible to objectively identify an acceptable velocity loss or the heaviest load that can be lifted within a specific velocity range.

The data shown in Tables 1 and 2 revealed that an ideal training load could not be identified for the group average when searching for a load associated with a velocity decrease that was not greater than the variation observed during the unloaded jumps. In addition, only three participants, or 25% of the sample, performed loaded jump squats with an acceptable velocity loss according to that process (Table 2). When considering the 10% velocity loss threshold, none of the load conditions coincided with a velocity loss less than that threshold at the group average level. At the individual level, the 15% load was the only intensity where the velocity decreased by 10% or less, but that occurred in only 5 participants (~42% of the sample). For the 20% velocity loss threshold, the 15% load fell within that range at the group average level. At the individual level, only the 15% and 30% loads could be considered ideal for 7 (~58%) and 2 (~17%), participants in the sample, respectively, while ideal loads could not be determined for 3 participants (~25%). With respect to suggested velocity ranges, none of the loads explored herein fell within the 0.75 m/s to 1.0 m/s range at the group average level. Interestingly, 10 participants (~83% of the sample) displayed velocities greater than 1.0 m/s across all loads, and only one participant performed the jump squat with the 45% load at a velocity within the 0.75 m/s to 1.0 m/s range. One participant performed the jump squat at a velocity within the 0.75 m/s to 1.0 m/s range at the 60% load. Based on these data, it is clear that practitioners are largely left to guess which velocity-based load to prescribe for jump squat training or accept that their load prescriptions are dependent on subjective recommendations rather than a systematic approach specific to their sample.

< Insert Figure 1 and Tables 1 & 2 About Here >

With respect to takeoff momentum, the magnitude of momentum at takeoff was greater in general during all loaded jumps compared to the unloaded jumps (Figure 2; Table 3). It cannot be ignored that both the load lifted and the movement velocity are important during ballistic exercise training. However, these momentum data, in conjunction with the aforementioned velocity data, suggest the mass of the athlete-load system can have a greater influence than the loss of velocity relative when seeking to provide positive "speed-strength" or explosiveness-based training stimuli. This is because the takeoff momentum data has a clear peak across loads for the group average and individual data (Figure 2; Table 3). Using a general visual inspection approach (34), the load condition with the greatest momentum (in general), which was the 30% load based on the current data, could be considered the ideal training load. The persistent presence of peak momentum across loads suggests the momentum-based approach is well-suited to objectively determine the ideal training load for jump squats. The remains true at the individual level, as the 15%, 30%, 45%, and 60% loads appear ideal for 1 (~8% of the sample), 5 (~42%), 2 (~17%), and 4 (~33%) participants, respectively (Table 3).

Importantly, the more objective approach to detect loads with percent gains of momentum that exceed the coefficient of variation from unloaded jumps to determine an appropriate load is a simple process. As shown in Table 4, 30% load was identified as the appropriate training load for the group's average participant, as it coincided with the largest "increase of momentum versus the unloaded jumps. This supports both the aforementioned visual inspection approach (34) and previous literature reporting this load to be effective during jump squat training for stimulating enhanced power production during jumping (13). More importantly, momentum-based training loads based on “increases of momentum were revealed in 10 participants, or ~83% of the sample. Interestingly, the 30% 1-repetition squat load was identified as the ideal training load in only four of the participants, or 25% of the sample. The 45% and 60% 1-repetition maximum squat load was identified as the ideal training load in two (~17%) and four (25%) participants in the sample, respectively. Thus, using system momentum can simplify load selection potential using both generalized and objective methods. Further, it can increase training efficacy for practitioners working with diverse athlete populations requiring individualized training prescriptions for their athletes.

< Insert Figure 2 and Tables 3 & 4 About Here >

Conclusions

We demonstrated that training loads for ballistic exercises (i.e., jump squats) can be easily determined via system momentum, and this process is likely to be more applicable than a velocity-based approach. System momentum reveals ideal training loads both visually on a graph (i.e., the magnitude of load associated with the greatest general increase of momentum) and via more objective measures revealing increases of momentum exceeding the typical amount of variation, both in a group of athletes and in individual athletes. Because the same cannot be stated for velocity due to the absence of a clear velocity pattern across loads, pivoting from use of velocity to system momentum can simplify programming for strength and conditioning professionals. This simplified approach may be especially useful for practitioners working with athlete populations requiring detailed, goal-specific training prescriptions that differ from other athletes on the same team. The data used to demonstrate the greater simplicity of load identification when using system momentum versus velocity were specific to jumping adaptations and the jump squat exercise. However, it is reasonable to presume that momentum-based load determinations can be effectively used for other ballistic exercises as long as the exercises do not involve voluntary concentric decelerations (e.g., bench press throws, cleans, etc.). Practitioners are encouraged to explore the use of system momentum in their training environments to maximize their ability to prescribe athlete-specific training programs.

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Tables

Table 1. Average takeoff velocities during jump squats of incremental loads (mean ± SD).

	Velocity at Each Load (m/s)				
Participant	**0%**	**15%**	**30%**	**45%**	**60%**
1	2.07 ± 0.30	2.01 ± 0.27	1.60 ± 0.03	1.27 ± 0.05	1.00 ± 0.18
2	2.74 ± 0.10	2.56 ± 0.20	2.15 ± 0.20	0.92 ± 0.80	0.36 ± 0.62
3	2.51 ± 0.03	2.28 ± 0.17	2.01 ± 0.05	1.80 ± 0.09	1.65 ± 0.07
4	2.46 ± 0.11	1.90 ± 0.22	1.75 ± 0.21	1.26 ± 0.24	1.40 ± 0.41
5	2.73 ± 0.07	2.44 ± 0.18	2.12 ± 0.06	1.81 ± 0.10	1.97 ± 0.12
6	2.98 ± 1.24	2.44 ± 0.66	1.87 ± 0.13	1.59 ± 0.05	1.22 ± 0.18
7	2.49 ± 0.10	2.50 ± 0.21	1.87 ± 0.07	1.77 ± 0.04	1.31 ± 0.07
8	2.69 ± 0.31	2.15 ± 0.15	1.93 ± 0.01	1.55 ± 0.29	1.40 ± 0.14
9	2.39 ± 0.04	2.11 ± 0.31	1.90 ± 0.15	1.55 ± 0.11	1.27 ± 0.19
10	2.93 ± 0.26	2.21 ± 0.07	2.13 ± 0.06	1.79 ± 0.07	1.46 ± 0.06
11	2.54 ± 0.09	2.39 ± 0.02	2.12 ± 0.04	1.87 ± 0.09	1.56 ± 0.03
12	2.82 ± 0.10	2.41 ± 0.04	2.15 ± 0.24	1.87 ± 0.15	1.77 ± 0.29
Group	2.61 ± 0.25	2.28 ± 0.21	1.97 ± 0.18	1.59 ± 0.30	1.36 ± 0.41

Notes – 0%, 15%, 30%, 45%, and 60% represent loads relative to each participant’s 1-repetition maximum squat; Average: average across three repetitions (for participants) or across participant averages (for group); SD: ± one standard deviation across three repetitions (for participants) or across participant averages (for group).

Table 2. Velocity losses and loss thresholds for jump squats of incremental loads.

		Velocity Loss at Each Load (%)			
Participant	CV Threshold	15%	30%	45%	60%
1	14.4	**-2.9***	-23.0	-38.7	-51.9
2	3.5	-6.7	-21.7	-66.3	-87.0
3	1.2	-9.2	-19.8	-28.3	-34.4
4	4.4	-22.5	-28.7	-48.9	-43.2
5	2.7	-10.7	-22.5	-33.5	-27.9
6	41.6	-18.0	**-37.1***	-46.8	-59.1
7	4.2	**0.5***	-24.9	-28.7	-47.3
8	11.5	-20.1	-28.5	-42.5	-48.0
9	1.6	-11.4	-20.5	-35.1	-46.7
10	8.8	-24.4	-27.4	-39.0	-50.2
11	3.6	-5.9	-16.5	-26.4	-38.7
12	3.6	-14.5	-23.8	-33.5	-37.3
Group	8.4 ± 11.2	-12.2 ± 7.9	-24.5 ± 5.4	-39.0 ± 11.2	-47.6 ± 15.0

Notes –15%, 30%, 45%, and 60% represent the jump squat loads relative to each participant’s 1-repetition maximum squat; CV% Threshold: coefficient of variation across repetitions, used to establish the maximum acceptable velocity decrease for load prescription; *: The ideal training load, defined as the highest load at which the velocity loss does not exceed the CV Threshold; Ideal training loads, when detected, are indicated as the greatest jump squat load characterized by a velocity loss less than the CV Threshold.

Table 3. Average takeoff momenta during jump squats of incremental loads (mean ± SD).

	Momentum at Each Load (kgm/s)				
Participant	**0%**	**15%**	**30%**	**45%**	**60%**
1	177.07 ± 41.08	223.11 ± 17.30	**232.95 ± 4.12**	218.16 ± 5.97	195.13 ± 32.49
2	205.61 ± 4.01	247.68 ± 8.48	**266.64 ± 10.13**	152.66 ± 132.21	66.43 ± 115.07
3	203.10 ± 2.91	227.47 ± 13.63	221.86 ± 6.17	225.31 ± 13.61	**229.57 ± 9.08**
4	206.46 ± 7.25	211.42 ± 4.07	206.42 ± 9.01	186.31 ± 14.46	**228.90 ± 61.24**
5	246.79 ± 6.95	270.12 ± 17.74	282.88 ± 6.71	274.98 ± 4.23	**312.51 ± 16.55**
6	239.10 ± 77.51	**248.34 ± 53.80**	239.26 ± 15.69	230.47 ± 3.32	201.62 ± 27.19
7	197.97 ± 7.92	245.29 ± 17.27	241.08 ± 13.28	**251.84 ± 40.76**	214.91 ± 11.16
8	248.60 ± 26.41	241.75 ± 15.20	**260.11 ± 2.13**	240.62 ± 21.69	246.16 ± 24.34
9	307.01 ± 3.68	327.42 ± 41.58	**344.90 ± 24.08**	327.55 ± 6.62	302.92 ± 43.67
10	186.16 ± 11.39	186.56 ± 4.94	**198.96 ± 5.25**	195.00 ± 6.62	179.91 ± 5.27
11	223.33 ± 8.53	255.50 ± 1.34	261.79 ± 5.14	**268.93 ± 10.81**	252.92 ± 4.57
12	272.12 ± 8.26	280.31 ± 3.21	299.29 ± 30.69	295.78 ± 23.10	**307.50 ± 45.82**
Group	226.11 ± 38.02	247.08 ± 35.79	**254.68 ± 41.07**	238.97 ± 48.88	228.21 ± 67.68

Notes – 0%, 15%, 30%, 45%, and 60% represent loads relative to each participant’s 1-repetition maximum squat; Average: average across three repetitions (for participants) or across participant averages (for group); SD: ± one standard deviation across three repetitions (for participants) or across participant averages (for group); Bolded results represent the ideal training load, defined generally as the load associated with the greatest system momentum.

Table 4. Momentum gain and gain thresholds for jump squats of incremental loads.

		Momentum Gain at Each Load (%)			
Participant	CV Threshold	15%	30%	45%	60%
1	23.2	26.0	**31.6***	23.2	10.2
2	2.0	20.5	**29.7***	-25.8	-67.7
3	1.4	12.0	9.2	10.9	**13.0***
4	3.5	2.4	0.0	-9.8	**10.9***
5	2.8	9.5	14.6	11.4	**26.6***
6	32.4	3.9	0.1	-3.6	-15.7
7	4.0	23.9	21.8	**27.2***	8.6
8	10.6	-2.8	4.6	-3.2	-1.0
9	1.2	6.6	**12.3***	6.7	-1.3
10	6.1	0.2	**6.9***	4.8	-3.4
11	3.8	14.4	17.2	**20.4***	13.3
12	3.0	3.0	10.0	8.7	**13.0***
Group	7.8 ± 9.9	10.0 ± 9.5	**13.2 ± 10.4***	5.9 ± 14.9	0.5 ± 24.5

Notes –15%, 30%, 45%, and 60% represent the jump squat loads relative to each participant’s 1-repetition maximum squat; CV% Threshold: coefficient of variation across repetitions, used to establish the maximum acceptable momentum increase for load prescription; *: The ideal training load, defined as the highest load at which the momentum gain exceeds the CV Threshold; Ideal training loads, when detected, are indicated as the greatest jump squat load characterized by an increase of momentum greater than the CV Threshold.

Figures

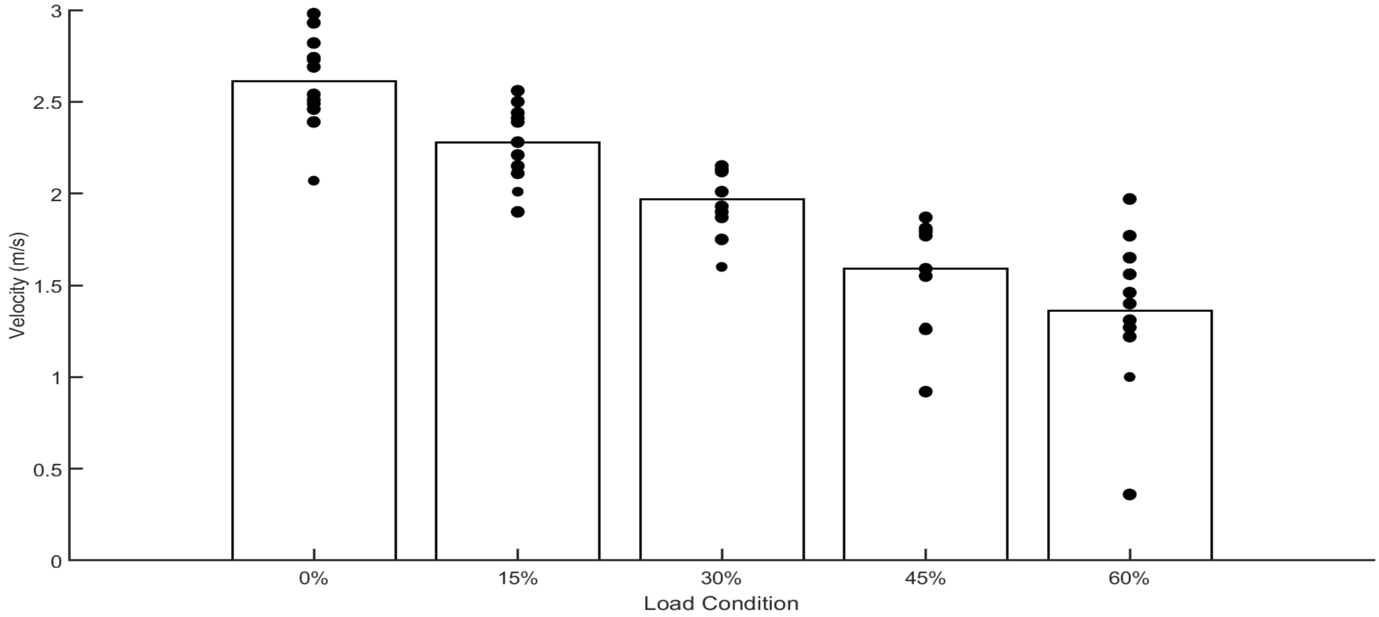

Figure 1. Takeoff velocities for unloaded and loaded jump squats (mean ± SD).

Note – Bars represent the average calculated across participants; Dots represents the individual participant averages calculated across repetitions.

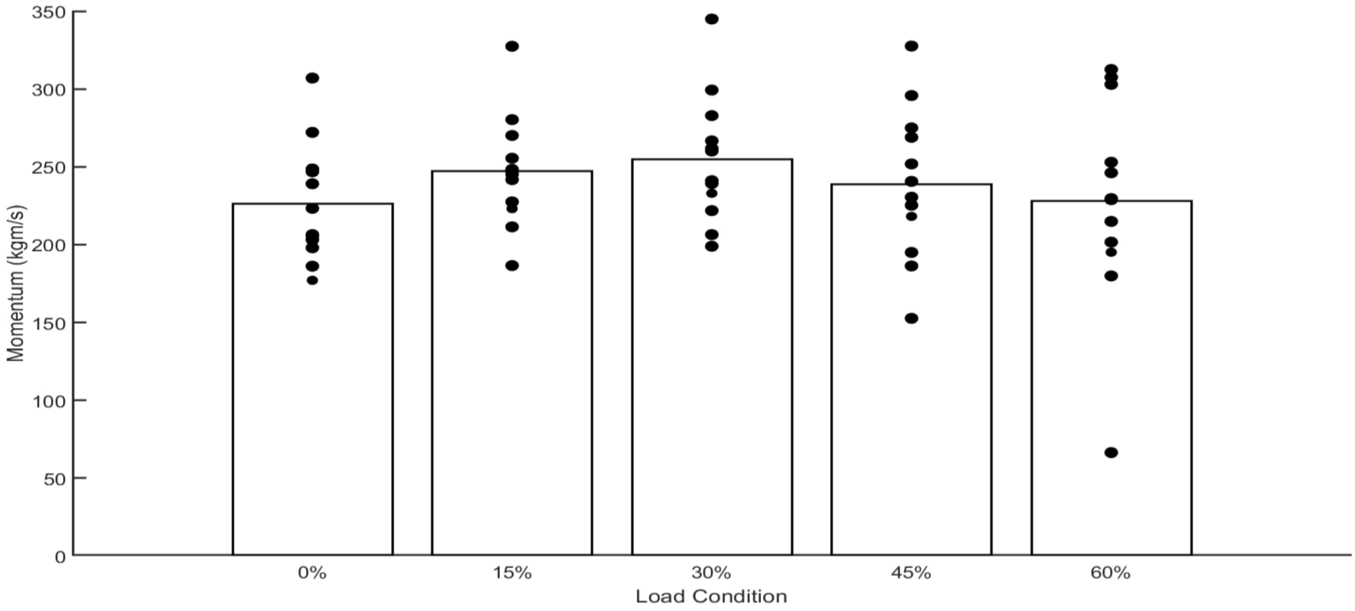

Figure 2. Takeoff momenta for unloaded and loaded jump squats (mean ± SD).

Note – Bars represent the average calculated across participants; Dots represents the individual participant averages calculated across repetitions.