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Determining the Threshold of Unweighting in Squat Jumps: A Study on Jump Height and Unweighting Amplitude

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Abstract

Agar-Newman, DJ, Funk, S, Cavin, E, Geneau, MC, Tsai, MC, and Klimstra, M. Determining the threshold of unweighting in squat jumps: a study on jump height and unweighting amplitude. *J Strength Cond Res* 39(3): 295–299, 2025—Squat jumps (SJs), involving only an upward propulsive phase, are commonly used in athletic assessment and research. Unfortunately detecting an unweighting phase before the upward propulsive phase is typically done subjectively by observing the athlete or inspecting the force–time trace, and there is no clearly established threshold of unweighting for a valid SJ. This reliance on subjectivity to determine a valid SJ has the potential to result in misleading findings or incorrect training interventions. Therefore, the aim of this study was to determine at what threshold of unweighting does SJ height increase. To answer this question, 56 female athletes, mean (±*SD*) body mass (BM) 76.26 ± 12.40 kg, height 1.68 ± 0.06 m, age 22.23 ± 1.47 years performed 936 SJs, under 4 different external loads. Squat jumps were divided into 6 separate groups based on the amplitude of unweighting relative to BM and an analysis of covariance was run with jump height as the dependent variable, unweighting group as the fixed factor, and external load as a covariate. There was a significant difference in jump height (F (5,930) = 13.65, $p < 0.01$) between unweighting groups while controlling for external load. Post hoc testing using Dunnett test showed that all SJ unweighting thresholds >2% BM ($p < 0.01$) resulted in an increased jump height from the threshold of ≤1% BM. Therefore, to maintain the validity of SJs as a measure, a threshold of 2% BM for unweighting amplitude is recommended. Adhering to this threshold will eliminate subjectivity in identifying valid SJs and potentially enable practitioners to automate the process using algorithms.

Key Words: counter movement, concentric, testing

Introduction

Comprehensive strength testing to determine an athlete's strengths and weaknesses is essential for effective training program design (27,29,31). Strength is defined as an individual's ability to produce force and can be expressed in multiple ways such as maximal isometric strength, explosive strength, maximal heavy dynamic strength, fast maximal dynamic strength, and reactive strength (15). Ballistic actions involving jumping and throwing tasks (29) are one method of assessment used by practitioners to gain insight into an athlete's force production abilities.

Jumping tasks, often performed on force plates, are used to measure fast maximal dynamic strength (15), power (20,37) and neuromuscular status (4). The squat jump (SJ) and countermovement jump (CMJ) are common jumping tasks used by practitioners and have been shown to be valid and reliable (26). The SJ is used to measure an athletes' rate of force development and ability to produce power using primarily a concentric muscle action (27,31,41). To complete an SJ, an athlete assumes a squat position with a knee angle of ≈90° held under isometric conditions for 3 seconds before jumping as high as possible (37). Holding the squat position and ensuring no unweighting phase (period where the force trace drops below body mass [BM]) before commencing the upward propulsive phase of the movement is essential, because it puts a unique constraint on the muscle's ability to produce force, such as removing the ability to use the stretch-shortening cycle (3,6,40). Conversely, in a CMJ, the athletes begin the movement with an unweighting phase, lowering their center of gravity rapidly before jumping as high as possible. This unweighting phase may allow the athlete to store and use elastic energy in the parallel and series elastic components present in the muscle and tendon, operate through a more optimal region of the force–muscle–length curve, allow the muscle to work at an optimal velocity, produce more work, increase electrical activity in the muscle, and reduce muscle slack (2,40), resulting in higher jump heights when than the SJ (2,3,24,38,40).

It is posited that a comparison of an athlete's SJ and CMJ ability (often called the eccentric utilization ratio [EUR]) can provide unique insights into an athlete's neuromuscular status and training adaptations (11,28). The difference in height between the SJ and CMJ potentially highlights an athlete's ability to use the stretch shortening cycle action (41) or other training areas of opportunity such as poor muscle activation (40) and rate of force development (23) in the case of a poor SJ performance relative to the CMJ. Further tracking training-induced adaptations through monitoring EUR has shown potential in higher trained populations (28) but not college level athletes (11). Because

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completing an unweighting phase before jumping leads to an increased jump height relative to starting from a static position, it is paramount practitioners check for an unweighting phase in SJs to prevent an inflation of jump height and ensure that the measurement is unique from the CMJ.

Unfortunately, achieving compliance with SJ protocols is challenging (37) and there is a lack of consensus on how to define the unweighting phase. For example, studies using force plates use different method to assess the validity of SJs. These include a downward displacement of 0.02 m (36), an unweighting in the ground reaction force of 5% BM (13,33) or 10% BM (9). Furthermore, an unweighting greater than or equal to 10% BM or decrease of greater than or equal to 10% in squat displacement before the initiation of the upward propulsive phase has been used (30). Other more subjective methods such as no visible unweighting determined by inspection of the force–time trace by a practitioner (21–23,32) and subjective visual observations for downward motion (5,8,25,35) have also been used. Finally, some studies do not specify exclusion criteria for valid SJs (7,9,14). This reliance on subjectivity to determine a valid SJ has the potential to result in misleading findings or possibly incorrect training interventions. Because 99.2% of SJs have some unweighting phase (37), it is important to determine at what threshold of unweighting jump height becomes inflated. Establishing a clear threshold for unweighting in the SJ would allow the use of algorithms for the detection of unweighting and remove the potential for subjectivity in detecting valid SJs. Therefore, the purpose of this study was to determine at what amplitude of unweighting, determined as percentage of BM, does SJ height increase. Because an unweighting phase leads to increased jump height, it was hypothesized that SJ height would increase with larger amplitudes of unweighting (Ha) with the null hypothesis that amplitude of unweighting would not increase SJ height (Ho).

Methods

Experimental Approach to the Problem

To assess at what threshold of amplitude of unweighting jump height increases during the SJ, a retrospective cohort study design was used. Anonymized SJ testing data were used from pre- and postseason testing sessions in a group of varsity rugby athletes. Amplitude of unweighting, determined as the lowest point in the force–time trace before the upward propulsive phase and presented as a percentage relative to BM, was the chosen measure for unweighting because it has previously been used to define unweighting (30) and is more robust to different algorithms used to identify the start of a jump such as unweighting impulse. Squat jumps were grouped based on the amplitude of unweighting that proceeded the jump. The dependent variable was jump height, and the independent variable was unweighting group. External load (weight on a barbell) was included as a covariate because practitioners often perform SJs under loaded conditions (1,34,39) and, therefore, accounting for the impact of external load was considered important. Because 99.2% of SJs have some unweighting phase (37), the unweighting threshold of ≤1% BM was used as the measure of a "good" SJ to which other unweighting thresholds were compared with.

Subjects

Fifty-six university female rugby athletes, mean ± *SD*, BM 76.26 ± 12.40 kg, height 1.68 ± 0.06 m, age 22.23 ± 1.47 years (range 17.88–23.87 years), were sampled for this study. Athletes were strength training 2 times per week (see Table 1 for a sample program) and regularly used bilateral jumps as part of their training regimen and testing battery. To be included in the study, all athletes were required to be free of injury and were allowed to stop testing at any point. All subjects gave their informed consent to partake in this study, and ethical approval for the study was obtained from the University of Victoria's Human Research Ethics Board and complied with the principles outlined in the Declaration of Helsinki.

Table 1
Typical strength session.*

Exercise	No. of sets	No. of repetitions
Jumping action	2–3	3–6
Clean variation	5–6	3–5
Lower body push or pull	5–6	3–7
Upper body push or pull	5–6	3–7
Individual supplemental exercise 1	2–3	11–15
Individual supplemental exercise 2	2–3	11–15
Individual supplemental exercise 3†	2–3	11–15

*Second year athletes performed the higher set ranges and lower repetition ranges.
†Only second year athletes performed the third supplemental exercise.

Procedures

Testing was conducted during the preseason and postseason periods when rugby volume was minimal. The testing was part of a wider test battery conducted as the only session of the day, taking place between 16:00 and 18:30 PM. The testing day consisted of a 20-minute warm-up consisting of 10 minutes of general activity through multiple planes to elevate body temperature and a 10-minute specific warm-up consisting of A-Skips, A-Runs, Straight Leg Runs, and 3 sprints of increasing intensity. Testing consisted of 2 × 40 m sprints of maximal intensity with approximately 5 minutes between sprints; heights were collected during the rest period. This was followed by a 5-minute walk to the biomechanics laboratory where athletes performed the jump testing. Jump testing was preceded by a specific warm-up of 3 CMJs akimbo, 3 minutes rest, then 3 CMJs akimbo approximately 3 minutes before commencing testing.

Jump Testing. Bodyweight was measured using 2 bilaterally mounted force plates (OR6-7; AMTI, Watertown, MA) before each jump. The plates were zeroed before the subject stepping on and once on the plates, the average force during the quiet standing period was selected then divided by 9.81 $m \cdot s^{-2}$ to determine the system weight (BM + external load), the external load was then subtracted from the system weight to determine BM.

The testing consisted of 3 CMJs with arms akimbo as part of the subjects regular testing battery. This was followed by the SJs. For the SJs, the subjects lowered themselves to a standardized depth of 0.50 m. This was confirmed by a rubber band positioned over the posterior edge of the force plate, which equated to a knee angle of ≈90°. A 3-second pause was initiated before commencing the upward propulsive portion of the jump. The subjects were instructed to jump for maximal height. The SJs were performed across 4 loads, beginning at 0.50 kg (doweling across the shoulders), and progressed by 15 kg increments unless the athlete was unable to jump over 0.10 m or technical proficiency was compromised as assessed by a National Strength and Conditioning Association Certified Strength and Conditioning

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Specialist. At each load, the subject performed 3 attempts with 10–15 seconds between jumps and 3 minutes between loads. Rogue Fitness barbells and plates (Columbus, OH) were used for all loaded SJs. All jumps were collected using AMTI (OR6-7; AMTI) force plates sampling at 1,000 Hz, and data were processed using custom script written in LabVIEW 2015 National Instruments (Austin, TX) software using the impulse–momentum method (24). Raw force–time data from each jump trial were filtered using a fourth-order Butterworth filter with a low-pass cutoff frequency of 50 Hz. The end of the unweighting period was identified as the first BM crossing moving backward from the peak force of the jump. The start of the unweighting period was identified as the next BM crossing moving backward from the end of the unweighting period. The amplitude of unweighting was the lowest point in the force–time trace between the start and end of unweighting period and presented as a percentage of BM. Test–retest reliability in our laboratory for SJ height demonstrated an intraclass correlation of 0.982 (0.931–0.995) and typical error of measurement of 0.02 m for jump height.

Statistical Analyses

Nine-hundred thirty-seven SJs were used for the analysis. The statistics were conducted in JASP (version 0.17.1; Amsterdam, Netherlands). The SJs were grouped by unweighting amplitude into 6 groups by increments of 1% with the last group consisting of jumps with an unweighting amplitude >5% BM (Table 2). The external loads ranged between 0.5 and 45 kg. To determine the threshold of unweighting that affected jump height, an analysis of covariance (ANCOVA) was run with jump height as the dependent variable, unweighting group as the fixed factor, and external load as a covariate. Alpha was set at 0.05. Assumptions were checked using Levene test for equality of variance and investigating the Q-Q Plot for normality. Dunnett test was used to determine significant differences between parameter estimates at each unweighting threshold and the amplitude of unweighting ≤1% BM group because of the risk of type I error while making multiple comparisons.

Results

The one-way ANCOVA compared the different unweighting thresholds while controlling for external load. Levene test and the Q-Q Plot showed normality in jump height. There was a significant difference in jump height ($F(5,930) = 13.65$, $p < 0.01$) between unweighting thresholds while adjusting for external load, however, the effect ($\eta_p^2 = 0.03$) is trivial (12). External load also had a significant effect ($\eta_p^2 = 0.62$) on jump height ($F(1,930) = 1{,}648.46$, $p < 0.01$). Dunnett test showed that the SJ unweighting threshold of ≤1% BM was significantly different from groups beginning at >2% BM threshold ($p < 0.01$), and all thresholds larger than this (refer to Table 3). Comparing the estimated marginal means showed that the unweighting thresholds >2% BM resulted in higher jump heights when compared with the ≤1%BM threshold, refer to Table 4.

Table 2
Descriptives—flight height (m).*†

Unweighting group	*N*	Mean ± *SD*
≤1% BM	316	0.14 ± 0.05
>1% and ≤2% BM	290	0.15 ± 0.05
>2% and ≤3% BM	152	0.16 ± 0.05
>3% and ≤4% BM	59	0.16 ± 0.06
>4% and ≤5% BM	36	0.19 ± 0.06
>5% BM	84	0.20 ± 0.06

*BM = body mass.
†Measurements in meters.

Table 3
Post hoc comparisons for unweighting groups.*

Comparison groups	Mean difference (m)	*SE* (m)	*t*	$p_{dunnett}$
≤1% BM to				
>1% and ≤2% BM	5.28×10^{-3}	4.21×10^{-3}	1.26	0.66
>2% and ≤3% BM	0.02	5.11×10^{-3}	3.47	2.68×10^{-3}†
>3% and ≤4% BM	0.02	7.34×10^{-3}	3.33	4.48×10^{-3}†
>4% and ≤5% BM	0.05	9.10×10^{-3}	5.04	<0.001‡
>5% BM	0.06	6.35×10^{-3}	9.25	<0.001‡

*BM = body mass.
†$p < 0.01$.
‡$p < 0.001$.

Discussion

The purpose of this study was to determine at what threshold of unweighting, jump height increases. The results rejected the null hypothesis and confirmed the alternative hypothesis, indicating that SJs with an amplitude of unweighting >2% BM result in significantly higher jumps than SJs with an amplitude of unweighting ≤1% BM while controlling for the effect of external load (Table 3). This finding has an impact on practitioners seeking to remove subjectivity from their identification of "good" SJs to use in research or to influence the design of training programs. Furthermore, the threshold of >2% BM could also be used in algorithms to automate the process of detecting SJs where athletes fail to adhere to the SJ protocol.

The difficulty of detecting compliance to SJ protocols has previously been noted with gross visual observation by practitioners only detecting 61.6% of trials with unweighting, despite 89.6% of SJ trials containing a small unweighting (37). Furthermore, it has been found that approximately 45.8% of jumps have unweighting amplitudes >10% BM as detected by force plates, highlighting the high frequency that unweighting occurs before the upward propulsive phase of the SJ (37). In contrast, our study found that only 8.96% of trials had an unweighting amplitude >5% BM. The reduced frequency of large unweighting periods found in our study likely highlights the importance of having subjects perform jumps as part of their regular training regimen and familiarity with the testing protocol, because the presence of a large unweighting period presents a unique threat to the validity of the SJ height. As this

Table 4
Marginal means for unweighting group.*†

Unweighting group	Marginal mean	95% CI for mean difference Lower–upper	*SE*
≤1% BM	0.15	0.14–0.15	1.76×10^{-3}
>1% and ≤2% BM	0.15	0.15–0.15	1.83×10^{-3}
>2% and ≤3% BM	0.15	0.15–0.16	2.52×10^{-3}
>3% and ≤4% BM	0.16	0.15–0.17	4.05×10^{-3}
>4% and ≤5% BM	0.17	0.16–0.18	5.20×10^{-3}
>5% BM	0.18	0.17–0.18	3.44×10^{-3}

*CI = confidence interval; BM = body mass.
†Measurements in meters.

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study showed, even small unweighting amplitudes result in an increase in jump height while holding constant the effect of external load (Table 4).

Including SJ trials with small unweighting periods outside of the >2% threshold could influence practitioners' interpretation of SJ data. For example, force velocity profiles constructed using a CMJ result in larger calculated maximal power output, force, and velocity values (17). Furthermore, inflating the SJ height would affect the calculation of EUR, masking training-induced adaptations if practitioners are tracking EUR longitudinally like other studies (28). As this study showed SJs with an unweighting >1–2% BM do not result in increased jump height when compared with the criterion condition of ≤1% BM, it is likely that practitioners can include jumps in their analysis when investigating SJ data or for comparison with CMJ when investigating EUR. This aligns with findings using different methodology for detecting unweighting that determined a small downward displacement of 0.01–0.03 m did not increase jump height significantly (10).

One limitation of this study is that only the impact of unweighting on the primary outcome of an SJ height was investigated. It is possible that practitioners may want to do further investigations on the impact of unweighting on tertiary measures such as force, power, or average velocity collected from the SJ as these measures are often used in research (16,18,19,38). A second limitation of this study is that it was completed with a sample consisting of only female rugby athletes. Significant differences in the impact of unweighting on jump height have been found in different sports and genders (11,23). However, gender was found to have only a small effect on the difference between SJ and CMJ jump heights with men having larger differences than women (23). Further on an individual level, it is likely that unweighting periods will affect individual athletes differently as shown by observations from the Australian Institute of Sport (37). It is possible that these findings could affect the generalizability of the unweighting amplitudes found in this study. However, until research is conducted with different populations of athletes, it is recommended that an unweighting amplitude of 2% BM be used as the threshold to determine SJ compliance as it removes subjectivity in the detection process and unweighting >2% BM have been shown to significantly increase jump height.

Practical Applications

For the SJ to be a valid measure, it is essential that it is unaffected by an unweighting period before the upward propulsive phase and, therefore, a standardized threshold is required. Based on the findings of this article, an amplitude of unweighting threshold of 2% BM is recommended for practitioners to use. Squat jumps with an unweighting >2% BM should be excluded from analysis because of the affect this unweighting can have upon jump height. The adoption of this threshold will remove subjectivity from the analysis process and allow practitioners to use this threshold in algorithms to automatically detect valid SJs.

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