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Comparison of Start Detection Methods for the Countermovement Vertical Jump with Arm Swing

Sunny Park[1], Michael J. Stewart[1] and John R. Harry[1]
[1]Sport & Occupational Neuromechanics Laboratory, Texas Tech University, Lubbock, USA
Corresponding Author: john.harry@ttu.edu

ABSTRACT

Start detection methods for force-time data analyses of the countermovement vertical jump with arms akimbo (CMJ) have been applied to the CMJ with an arm swing (CMJ-AS). However, little is known regarding the implications of different start detection methods on derived CMJ-AS outcome measures. We compared CMJ-AS start locations that were identified by four detection methods: 1) (body weight [BW] ± 5 standard deviations [5SD]), 2) (maximum [max] BW + 5SD or minimum [min] BW – 5SD), 3) (BW ± 2.5%), and 4) (max BW + 2.5% or min BW – 2.5%). Twenty-two collegiate male basketball players (20.23 ± 2.00 yr, 1.99 ± 0.07 m, 93.79 ± 8.48 kg) performed 3 CMJ-AS trials while vertical ground reaction force (vGRF) data was recorded. A one-way repeated measures ANOVA ($\alpha \leq 0.05$) supplemented by Cohen's *d* effect sizes compared time to takeoff (TTT), unloading phase metrics, and CMJ-AS start vGRF value amongst the methods. TTT was longer for method 1 (0.99 ± 0.16 s) than methods 2 (0.94 ± 0.17 s, $p < 0.01$, $d = 0.29$) and 4 (0.92 ± 0.19 s, $p = 0.01$, $d = 0.43$). Unloading time was longer for method 1 than methods 2 ($p < 0.01$, $d = 0.16$) and 4 ($p < 0.01$, $d = 0.22$) and longer for method 3 than method 4 ($p = 0.02$, $d = 0.21$). Unloading force and rate of force development were different between methods 1 and 2 ($p \leq 0.01$, $d = 0.17$) and methods 3 and 4 ($p \leq 0.01$, $d = 0.21$-0.22). There was no difference amongst methods in CMJ-AS start vGRF value. Erroneous start identification rate was lowest for method 4 (3.03%). When analyzing the CMJ-AS, max BW + 2.5% or min BW – 2.5% is recommended to improve start detection and avoid compromised unloading phase metrics.

INTRODUCTION

Force platforms are data collection instruments used to record ground reaction forces (GRF) during physical performance tasks (29). A common movement performed on force platforms is the countermovement vertical jump (CMJ). This task is performed with subjects standing still at the start, lowering their center of mass (COM) to a self-selected or prescribed depth, and then jumping vertically and landing on the force platforms (24). CMJ assessments with force platforms have become commonplace in sport-related test batteries conducted by researchers and practitioners, as they provide many valuable physical performance output, neuromuscular function, and external force production strategy metrics (2). This information may then be subsequently used to assist in the designing of resistance training, rehabilitation, or workload interventions.

The CMJ is commonly performed with the hands on the hips (i.e., arms akimbo) (1,6,14,16,19,32). This protocol is widely used in many research laboratories and high-performance environments to control for upper body influences on performance. However, the contribution of arm swing to CMJ (CMJ-AS) performance (3,7,23) can also be of interest to coaches and practitioners from an ecological validity and sport specificity standpoint because many sports, such as basketball and volleyball among others, require athletes to not only jump but to also reach overhead when airborne.

Analysis of the CMJ-AS requires an accurate detection of the start of the movement, with errors subsequently affecting important temporal-related metrics. For example, unloading time, which has been shown to differentiate good from poor jumpers (13), depends on the accurate identification of the start of the CMJ-AS. Another notable metric that has been used when assessing athletic performance is reactive strength index modified (RSImod) (33). This metric is the ratio of jump height to time to takeoff (TTT). An inaccurate detection of the start of the jump will compromise TTT and thus RSImod. For example, an inaccurate early detection of the start will increase TTT and thus decrease RSImod, thereby suggesting a decrease in an individual's measure of explosiveness (33).

Different detection methods have been used to identify the start of a CMJ (1,15,22,25,28). The most used methods originated or were recommended from two studies. Meylan and colleagues demonstrated that GRF change exceeding 2.5% of body weight (BW) was the most effective threshold to use for CMJ force-time analysis (25). Their conclusion was based on a comparison with other thresholds such as 5% BW and 10% BW. Owen et al. (28) later suggested using BW ± 5 standard deviations (5SD) of the GRF during quiet standing (i.e., the time when calculating BW). Their rationale was that the method minimizes the probability of an erroneous detection of the start of the countermovement. Harry et al. (10) recently adapted the threshold used by Owen et al. (28) by using the maximum (max) GRF value during the BW period ± 5SD, as the GRF during the quiet standing period can fluctuate to values exceeding the calculated BW + 5SD. In addition to the max GRF value during the BW period, the minimum (min) GRF during the BW period has also been used as a baseline to identify the start of the CMJ (34,35).

It has been demonstrated that force-time curve characteristics between the CMJ and the CMJ-AS differ in shape and magnitude at various time points during the movement (8,26). However, there is a lingering issue related to recent work, as the application of CMJ start detection methods recommended specifically for akimbo jumps have been applied to the CMJ-AS without a clear justification (12,21). To date, there is not much known regarding the accuracy of their application to the CMJ-AS, particularly surrounding their similarities, abilities to detect a start without error, or both. Therefore, the purpose of this study was to demonstrate whether four start detection methods lead to different and potentially erroneous identifications of the start during the CMJ-AS. Specifically, the investigated methods were:

Method 1: BW ± 5SD
Method 2: max BW + 5SD or min BW – 5SD
Method 3: BW ± 2.5%
Method 4: max BW + 2.5% or min BW – 2.5%

It was hypothesized that the four methods would yield different start locations of the CMJ-AS. It was also hypothesized that method 4 (max BW + 2.5% or min BW – 2.5%), which has been adapted based on the works of Harry et al. (10), Wade et al. (35), and Meylan et al. (25), and method 2 (max BW + 5SD or min BW – 5SD) will provide the fewest erroneous identifications of the start of a CMJ-AS. We tested this hypothesis due to the possibility that the maximum vertical GRF (vGRF) recorded during the quiet standing period can be greater than the calculated BW + 5SD (10), particularly when participants can move their arms freely at the start of the countermovement.

METHODS

Experimental Approach to the Problem

Applying CMJ start detection methods to the CMJ-AS without adequate justification may lead to erroneous results. As this is common practice in contemporary research and practice, we compared the effect of four start detection methods on TTT and the CMJ-AS start vGRF value to determine whether the start of the CMJ-AS is identified at the same instant in time. Unloading phase metrics (i.e., unloading time, unloading rate of force development, unloading force) were also analyzed to determine if temporal and kinetic metrics would differ between the start detection methods. We also sought to identify which method was least likely to identify an erroneous CMJ-AS start. A sample of collegiate male basketball players each performed 3 CMJ-AS trials. A one-way repeated measures design was employed to assess the statistical probability of agreement amongst the four start detection methods. This approach was carried out to provide researchers and practitioners with an objective comparison of start detection methods to provide clarity when analyzing CMJ-AS data.

Subjects

An a priori sample analysis using G*Power software determined the minimum sample size required for a repeated measures ANOVA (within factors) with $\alpha \leq 0.05$, 1-β = 0.9, and effect size = 0.30 was n = 22. As such, 22 NCAA Division I male basketball players were recruited to participate in the study. Testing occurred across two sport seasons. Subject demographic information is provided in Table 1. Basketball players were examined as the sport frequently requires jumping (30) with the arms reaching overhead, meaning the CMJ-AS may provide more value for the population than the CMJ with arms akimbo. At the time of testing all subjects were free of any injury, condition, or ailment that would have limited their ability to perform the CMJ-AS. Prior to completing any laboratory testing, subjects were informed of the testing benefits and risks before providing written informed consent as approved by the university Institutional Review Board in accordance with the Declaration of Helsinki.

Table 1. Subject demographics

Age (yr)	Height (m)	Body mass (kg)
20.23 ± 2.00	1.99 ± 0.07	93.79 ± 8.48

Procedures

Subjects completed all CMJ-AS trials during a single laboratory visit. Age, height, and body mass were recorded following completion of the informed consent process. Due to the unique subject population requirements, a dynamic warm-up was implemented by the team's strength and conditioning coach specific to the needs of each player. Up to 5 familiarization CMJ-AS trials were provided. All CMJ-AS trials were performed on two three-dimensional in-ground force platforms (OPT464508; Advanced Mechanical Technology, Inc., Watertown, MA) sampling at 1000 Hz and recorded in Vicon Nexus software (2.6; Vicon Motion Systems, Ltd., Oxford, UK). Subjects started each CMJ-AS trial in a vertical standing still position with feet approximately hip-width apart and arms hanging down by their side. Subjects were instructed to jump as fast and as high as possible using a preferred countermovement depth with an overhead arm swing to reach both hands as high as they could to improve ecological validity of testing. This allowed subjects to maintain their preferred arm swing style, such as a posterior swing leading to a forward and upward swing, promptly swinging upward and forward, or another strategy. Subjects performed 3 CMJ-AS trials with up to 2 minutes of rest between trials. To maximize data collection efficiency with the population, two consecutive CMJ-AS (i.e., rebound jump) were performed during each trial, but only the first jump was used for analysis.

Data Processing

Vertical GRF for the total body COM was calculated by summing the vGRF data from the two force platforms (i.e., left limb + right limb vGRF). A filter was not used, as the takeoff event is dependent on appropriate selection of the cutoff frequency, and different cutoff frequencies have been used for the CMJ (1,17,20,31). Body mass was then calculated as BW (i.e., mean vGRF in the first 500 ms of standing) divided by gravitational acceleration. The max BW and min BW values for methods 2 and 4 were established based on the absolute maximum and minimum vGRF, respectively, during this 500 ms standing period. The threshold values of 5SD and 2.5% were also calculated based on the vGRF data during the first 500 ms of standing. For each detection method, whichever conditional term occurred first (i.e., method 1: BW + 5SD or BW – 5SD; method 2: max BW + 5SD or min BW – 5SD; method 3: BW + 2.5% or BW – 2.5%; method 4: max BW + 2.5% or min BW – 2.5%) was deemed the start of the CMJ-AS and the CMJ-AS start vGRF value for a given trial. Although methods using the ± 5SD threshold typically also include a 30 ms backward search to establish the starting point for mathematical integration (28), it is not necessary here as it will only augment any difference amongst methods for when the start threshold was exceeded. Takeoff was defined as the time point when the summed vGRF decreased below 10 N (27). Time to takeoff was defined as the time between the initiation of the CMJ-AS based on the conditional terms of each of the four start detection methods and the time of takeoff. The unloading phase was defined as the initiation of the CMJ-AS in accordance with each of the four start detection methods and the local minimum vGRF (9). Unloading time therefore represents the time between the initiation of the CMJ-AS and the end of the unloading phase. Unloading yank, or rate of force development (RFD), was defined as the change in vGRF between the start and the end of the unloading phase divided by unloading time. Unloading force was defined as the average vGRF applied during the unloading phase. MATLAB software (R2023a; The MathWorks, Inc., Natick, MA) was used for data processing to obtain TTT, unloading time, unloading RFD, unloading force, and the CMJ-AS start vGRF value for each of the four start detection methods simultaneously for each individual trial.

Statistical Analysis

Mean and standard deviation values for each metric defined previously were calculated across all CMJ-AS trials for the four start detection methods. In addition, 95% confidence intervals were also calculated to provide an estimate for the interval within which the population mean exists. The probability that the difference amongst methods was due to random chance was determined using a one-way repeated measures ANOVA ($\alpha \leq 0.05$) conducted in IBM SPSS Statistics (version 29; IBM Corp., Armonk, NY). The assumption of local sphericity was examined with Mauchly's test. A violation of sphericity ($p \leq 0.10$) was corrected with Huynh-Feldt when epsilon was greater than or equal to 0.75 and with Greenhouse-Geisser when epsilon was less than 0.75. The uncorrected degrees of freedom and epsilon values were reported. The Sidak adjustment was used to control the familywise error rate of the post hoc comparisons. Cohen's *d* effect sizes (0.20 = small, 0.50 = medium, 0.80 = large) were used to determine the magnitude of the differences (4). All force-time curves were inspected using the crosshair region-of-interest (ROI) function in MATLAB, similar to Kipp et al. (18). Specifically, the horizontal line of the crosshair was aligned to the BW standing period while the vertical line was aligned to the noticeable increase (i.e., preload) or decrease (i.e., unload) in the vGRF in proximity to the local minimum. When a detection method identified a start that was not within recognizable proximity to the crosshair, it was deemed an erroneous start. Exemplary force-time curves are presented in Figures 1-5. Specifically, Figure 1 shows an example trial whereby all four start detection methods demonstrated agreement. Figures 2-5 provide example trials for when each detection method resulted in an erroneous identification of the start of the CMJ-AS to demonstrate how these were inspected and determined. Trials for which a start detection method resulted in an erroneous identification of the start were documented to obtain each method's erroneous start identification rate and

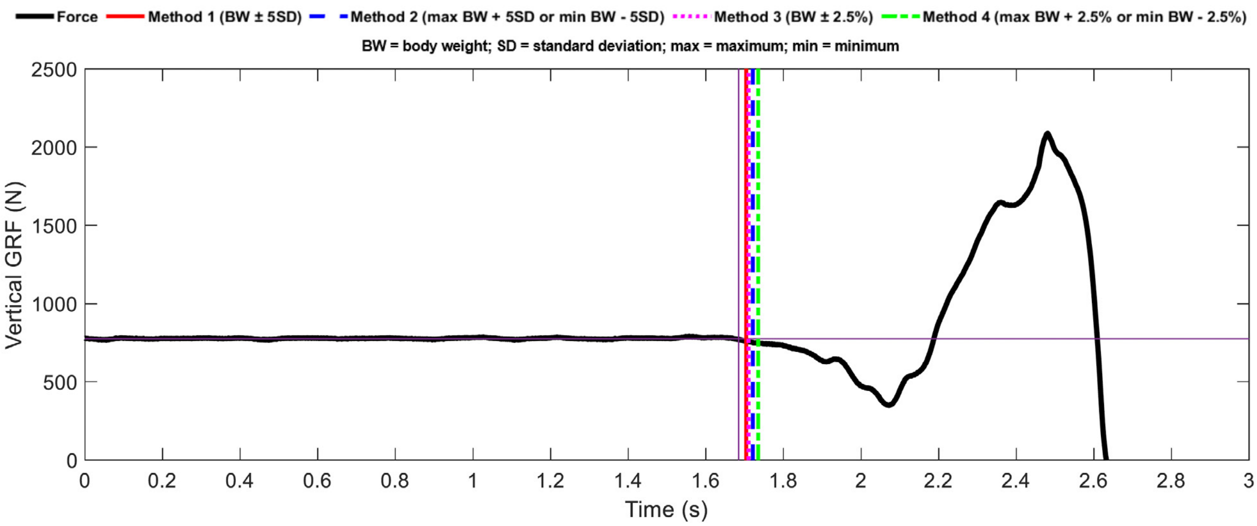

Figure 1. CMJ-AS force-time curve trial demonstrating agreement amongst all four start detection methods.

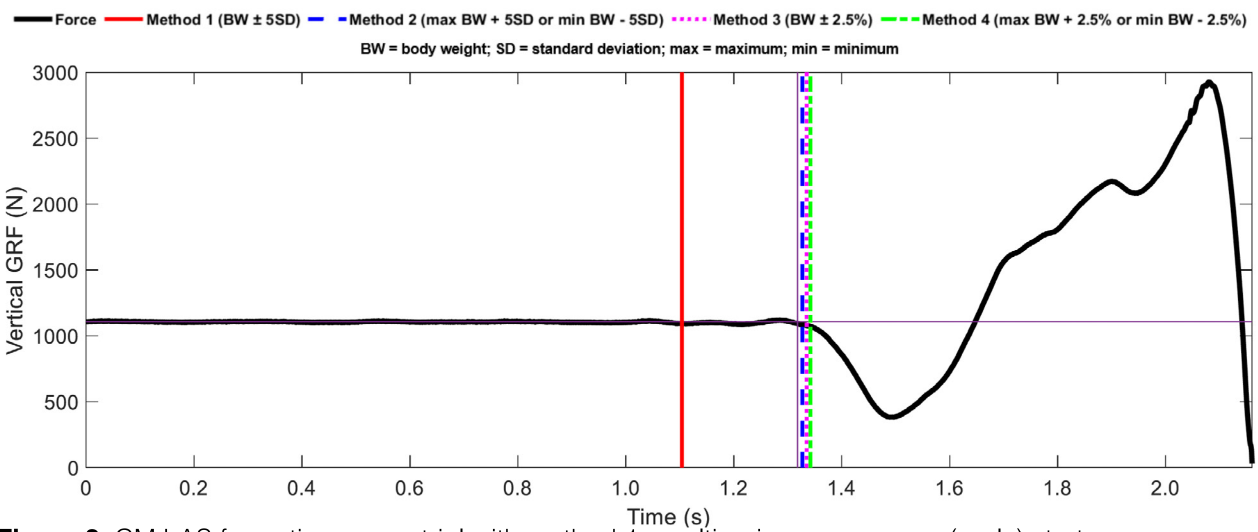

Figure 2. CMJ-AS force-time curve trial with method 1 resulting in an erroneous (early) start.

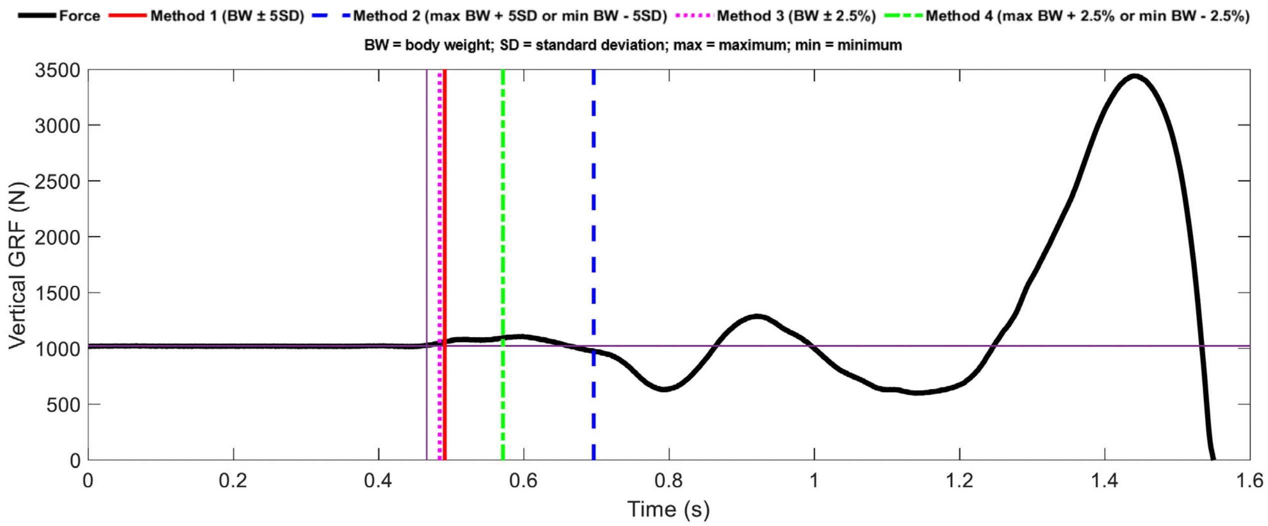

Figure 3. CMJ-AS force-time curve trial with method 2 resulting in an erroneous (late) start.

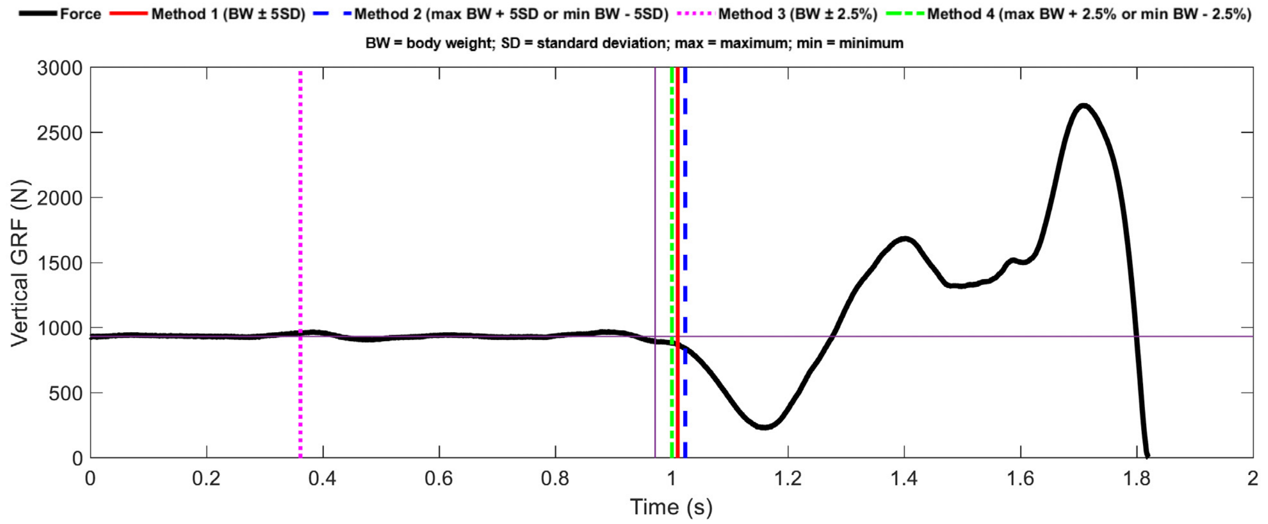

Figure 4. CMJ-AS force-time curve trial with method 3 resulting in an erroneous (early) start.

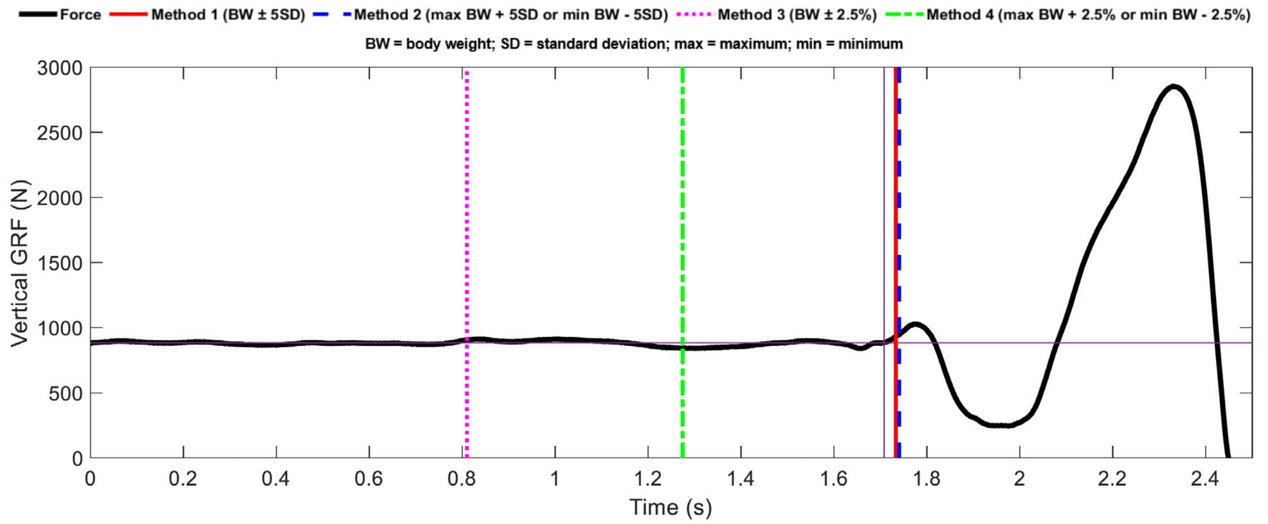

Figure 5. CMJ-AS force-time curve trial with method 4 (and method 3) resulting in an erroneous (early) start.

removed from analysis of unloading phase metrics. This was done to minimize the compromising effects of outliers when comparing methods that resulted in a similar identification of the start of the CMJ-AS for a given trial.

RESULTS

TTT and the CMJ-AS start vGRF value are presented in Table 2. The one-way repeated measures ANOVA ($\alpha \leq 0.05$) demonstrated TTT was affected by the start detection method, $F(3, 63) = 4.92$, $p = 0.02$, $\varepsilon_{GG} = 0.61$, $\eta_p^2 = 0.19$. TTT was longer for method 1 than methods 2 ($p < 0.01$, $d = 0.29$) and 4 ($p = 0.01$, $d = 0.43$), with a small effect size for both differences. The one-way repeated measures ANOVA ($\alpha \leq 0.05$) demonstrated the CMJ-AS start vGRF value was not affected by the start detection method, $F(3, 63) = 1.50$, $p = 0.24$, $\varepsilon_{GG} = 0.64$, $\eta_p^2 = 0.07$.

All unloading phase metrics are presented in Table 3. The one-way repeated measures ANOVA ($\alpha \leq 0.05$) demonstrated unloading time was affected by the start detection method, $F(3, 63) = 6.08$, $p = 0.01$, $\varepsilon_{GG} = 0.54$, $\eta_p^2 = 0.23$. Unloading time was longer for method 1 than methods 2 ($p < 0.01$, $d = 0.16$) and 4 ($p < 0.01$, $d = 0.22$) and longer for method 3 than method 4 ($p = 0.02$, $d = 0.21$). Cohen's d calculations indicated a small effect size for the difference in unloading time between methods 1 and 4 and methods 3 and 4.

The one-way repeated measures ANOVA ($\alpha \leq 0.05$) demonstrated unloading RFD was affected by the start detection method, $F(3, 63) = 4.25$, $p = 0.03$, $\varepsilon_{GG} = 0.59$, $\eta_p^2 = 0.17$. Unloading RFD was smaller for method 1 than method 2 ($p = 0.01$, $d = 0.17$) and smaller for method 3 than method 4 ($p = 0.01$, $d = 0.21$). Cohen's d calculations indicated a small effect size for the difference in unloading RFD between methods 3 and 4.

The one-way repeated measures ANOVA ($\alpha \leq 0.05$) demonstrated unloading force was affected by the

Table 2. TTT and the CMJ-AS start vGRF value for each start detection method (mean ± SD [95% CI])

Method	TTT (s)	CMJ-AS start vGRF value (N)
1	0.99 ± 0.16 [0.92 to 1.06]	925.76 ± 92.42 [884.79 to 966.74]
2	0.94 ± 0.17 [0.87 to 1.02] [a]	922.94 ± 93.17 [881.63 to 964.25]
3	1.00 ± 0.22 [0.90 to 1.10]	930.93 ± 91.51 [890.35 to 971.50]
4	0.92 ± 0.19 [0.83 to 1.00] [b]	927.25 ± 93.76 [885.68 to 968.82]

Notes - [a]: Significantly different than method 1 (p < 0.01); [b]: Significantly different than method 1 (p = 0.01); 95% CI = 95% confidence interval.

Table 3. Unloading phase metrics for each start detection method (mean ± SD [95% CI])

Method	Unloading time (s)	Unloading RFD (N/s)	Unloading force (N)
1	0.38 ± 0.18 [0.30 to 0.46]	-2188.49 ± 1470.01 [-2840.25 to -1536.72]	741.23 ± 124.09 [686.21 to 796.25]
2	0.35 ± 0.18 [0.27 to 0.43] [a]	-2447.30 ± 1594.48 [-3154.26 to -1740.35] [a]	720.57 ± 128.96 [663.39 to 777.75] [a]
3	0.38 ± 0.18 [0.30 to 0.46] [b]	-2209.57 ± 1489.12 [-2869.81 to -1549.33] [b]	740.86 ± 115.86 [689.49 to 792.23] [b]
4	0.34 ± 0.18 [0.26 to 0.42] [c]	-2533.76 ± 1671.50 [-3274.86 to -1792.66]	715.03 ± 123.30 [660.36 to 769.70]

Notes - [a]: Significantly different between methods 1 and 2 (p ≤ 0.01); [b]: Significantly different between methods 3 and 4 (p ≤ 0.02); [c]: Significantly different between methods 1 and 4 (p < 0.01); 95% CI = 95% confidence interval.

Table 4. Erroneous start identification rates for each start detection method

Method	Erroneous start identification rate (%)
1	16.67
2	9.09
3	10.61
4	3.03

start detection method, $F(3, 63) = 4.39$, $p = 0.03$, $\varepsilon_{GG} = 0.50$, $\eta_p^2 = 0.17$. Unloading force was larger for method 1 than method 2 ($p < 0.01$, $d = 0.17$) and larger for method 3 than method 4 ($p < 0.01$, $d = 0.22$). Cohen's *d* calculations indicated a small effect size for the difference in unloading force between methods 3 and 4.

Erroneous start identification rates are presented in Table 4. The rate was highest for method 1 and lowest for method 4.

DISCUSSION

The simultaneous application of four start detection methods to the CMJ-AS demonstrated differences in the identification of the start, thereby supporting our first hypothesis. Our hypothesis that methods 2 (max BW + 5SD or min BW – 5SD) and 4 (max BW + 2.5% or min BW – 2.5%) would provide the fewest erroneous identifications of the CMJ-AS start was partially supported. Methods 1 (BW ± 5SD) and 3 (BW ± 2.5%) had the highest erroneous start identification rates. Methods 2 and 4 had a comparable TTT, but method 4 had a lower erroneous start identification rate.

The four start detection methods are comparable in CMJ-AS start vGRF value. However, this result should be interpreted cautiously. For example, in Figure 2, method 1 resulted in a CMJ-AS start vGRF value of 1092.70 N while method 2 resulted in a CMJ-AS start vGRF value of 1085.57 N. This is a 0.65% difference, yet the TTT difference between the two methods was 0.22 seconds. This most importantly demonstrates that a comparable CMJ-AS start vGRF value will not always result in comparable temporal metrics.

The results indicate that the use of BW for the CMJ-AS is an inappropriate baseline for the start criterion. This is potentially due to greater movement artifact when arm swing is permitted, even when a subject is instructed to stand still prior to jump initiation (25). Filtering the data could be an approach to minimize vGRF fluctuations and movement artifact, but filtering can compromise detection of the takeoff event when the cutoff frequency is not appropriately selected (11). These factors may also explain why 5SD may be too conservative of a threshold value for the CMJ-AS, which is supported by our observation that the 2.5% BW threshold resulted in a lower erroneous start identification rate for method 4 compared to method 2.

Owen et al. (28) suggested that the use of 5SD would reduce the probability of a mistrigger for the initiation of a CMJ. However, based on the erroneous start identification rates, the use of their recommended criterion (BW ± 5SD) appears to be the least effective start detection method when applied to the CMJ-AS. It is important to acknowledge that the use of 5SD was claimed to reduce the probability of erroneous detection to 1 in every 1,744 trials (28). However, this probability is dependent on the 5SD threshold being obtained from a *perfectly* still quiet standing period, which is very unlikely with subjects particularly during the CMJ-AS. The significance of this is particularly relevant for researchers and practitioners choosing to study temporal-related CMJ-AS metrics, such as RSImod (5,18,33). Although jump height would not be different between methods, our results suggest using BW ± 5SD during a CMJ-AS assessment would lead to a lower RSImod due to a longer TTT.

We selected unloading phase metrics to supplement TTT to provide some insight into how CMJ-AS strategies can be misinterpreted when using inappropriate start detection methods. For instance, unloading time, which occurs from jump initiation until the reduction of vGRF immediately prior to the start of the eccentric phase, was found to be longer for method 1 compared to both methods 2 and 4, and longer for method 3 compared to method 4. Harry et al. (13) demonstrated the importance of unloading time to jump performance using only a BW – 2.5% threshold. Our results suggest their use of this start criterion may have potentially resulted in inaccurate detections of the start of the jump leading to erroneous unloading times. This could raise questions regarding the discussed importance of faster unloading strategies. However, it more importantly emphasizes the need for replication of published CMJ-AS studies using appropriate start detections to support or refute current conclusions regarding temporal metrics. While there was a difference in unloading RFD and unloading force between methods 1 and 2, the magnitudes of the differences were trivial-to-small at best. This suggests that researchers and practitioners should keep in mind potential issues with force metrics amongst start detection methods during unloading, but they are unlikely to have a meaningful impact on interpretations. Ultimately, unloading phase metrics should not be examined unless the user chooses to use either method 3 or 4 for the CMJ-AS start detection method.

The results also demonstrate that none of the four start detection methods are 100% accurate. As there does not currently appear to be a one-size-fits-all start detection method, researchers and practitioners are recommended to assess each force-time curve individually to accurately identify the start of a CMJ-AS. However, in a large team setting or if limited by either time or analysis constraints, this may not be a practically feasible option. It is in these situations that the use of method 4 (max BW + 2.5% or min BW – 2.5%) is the most effective at minimizing the erroneous detection of the start of the CMJ-AS.

A possible limitation to the study includes the use of a warm-up specific to each subject rather than a general warm-up for all subjects. This may challenge replication of the data collection methodology, but it does have ecological validity for the population represented by the sample. Additionally, the use of a rebound jump (i.e., first of two successive jumps) to study the CMJ-AS was a possible limitation. Specifically, the second jump may have potentially altered temporal and kinetic strategies when performing the first jump in comparison to the execution of a single CMJ-AS. However, this task was used to maximize data collection efficiency when working with a NCAA Division I basketball program. The rebound jump performed with arms akimbo has been demonstrated to result in a shorter TTT compared to a CMJ (36), and this may also apply to the CMJ-AS. However, because the four start detection methods were applied simultaneously to each individual trial, the use of a rebound jump did not affect the ability to identify differences amongst the four start detection methods.

CONCLUSION

This study demonstrated that blindly applying several traditional CMJ start detection methods to the CMJ-AS may result in an erroneous identification of the start. This will subsequently reduce the accuracy of TTT and make it difficult to compare how certain temporal or kinetic variables of interest (e.g., unloading time, unloading RFD, unloading force) may or may not contribute to an improvement in CMJ-AS performance. Therefore, when analyzing the CMJ-AS, to minimize an erroneous identification of the start, researchers and practitioners are recommended to use method 4 (max BW + 2.5% or min BW – 2.5%).

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CONFLICTS OF INTEREST

There are no conflicting relationships or activities.

FUNDING

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ETHICAL APPROVAL

Ethics for this study were approved by the university Institutional Review Board in accordance with the Declaration of Helsinki.

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