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Low-Pass Filter Effects on Metrics of Countermovement Vertical Jump Performance

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Abstract

Harry, JR, Blinch, J, Barker, LA, Krzyszkowski, J, and Chowning, L. Low-pass filter effects on metrics of countermovement vertical jump performance. *J Strength Cond Res* XX(X): 000–000, 2020—Countermovement vertical jump (CMVJ) studies using ground reaction force (GRF) data analyze either unfiltered (i.e., raw) or filtered data while providing little-to-no justification for the selected filtering process. Inappropriate filter choices can lead to inaccurate study results and erroneous interpretations. We examined the effects of not filtering GRF data in comparison with filtering data with various objectively and subjectively selected cutoff frequencies. Twenty-one collegiate male basketball players completed 3 maximal-effort CMVJ trials while GRF data were obtained from 2 force platforms. Countermovement vertical jump performance, explosiveness, power output, and neuromuscular function variables were compared among the following methods using one-way repeated-measures analyses of variance ($\alpha = 0.05$): no filtering (raw data), a standard 50-Hz cutoff (50 Hz), a visually determined cutoff frequency describing the frequency band containing the majority of the summed (visual inspection 1) or not-summed (visual inspection 2) GRF signal's frequency content, filtering the summed (99% signal power 1) or not-summed (99% signal power 2) GRF using a cutoff frequency retaining 99% of the signal power. The raw data method produced significantly shorter concentric phase times and significantly greater center of mass flight heights (~3%), modified reactive strength indices (RSI_{MOD}; ~4%), power outputs (~6%), and push-off distances (~4%) than 99% signal power 1 and 2 ($p < 0.05$). Discrete GRF and phase-specific yank magnitudes were not different among methods ($p \geq 0.05$). Importantly, no differences were detected between the raw data and 50 Hz methods for any variable ($p > 0.05$). Low-pass filtering is not necessary when analyzing GRF data from the CMVJ. However, a low-pass filter with a 50-Hz cutoff can remove noise without altering results when compared with raw data. Explicit methodological descriptions of filtering processes should always be provided to improve the integrity of future CMVJ analyses, comparisons among various studies' results, or both.

Key Words: ground reaction force, jumping, power production, rate of force development, smoothing

Introduction

The countermovement vertical jump (CMVJ) is a popular physical performance test because it is associated with strength, power, speed, agility, and physical readiness (4,9,29,47). Researchers have stated that an athlete's mechanical output and total body movement within the CMVJ phases should be focal points of quantitative assessments (15,31). This is because CMVJ phase durations and their associated force-time variables (e.g., yank or rate of force development) (27) can provide a greater understanding of an athlete's neuromuscular capabilities than the gross performance (i.e., jump height) of the task (31). Historical inconsistencies (3,8,13,25) and observed variability (30,34) of yank results might challenge how effective force-time characteristics are at revealing underlying mechanisms of CMVJ performance and neuromuscular ability. However, consistent use of functionally and mechanically sound CMVJ phases (15) should address inconsistencies and variability moving forward. Phase-specific mechanics should continue to be studied, so researchers and practitioners can improve translation of research findings to training and competition environments.

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Assuming appropriate CMVJ phases are used, data processing procedures may be the primary factor influencing whether dependent variables relate to jump performance or differ among individuals. This is because the ground reaction force (GRF) data used for analysis is a time-varying signal. Thus, recorded GRF data contain both desired information (i.e., the signal) and undesired information (i.e., high-frequency noise/measurement error) made up of electrical interference, artifacts from moving wires, crosstalk between force platform channels, or a combination thereof (11). A primary goal of data processing is to retain the signal while filtering out the noise (11). It is important to reduce noise in recorded GRF data because the GRF is used either directly or indirectly to calculate many movement features (e.g., center of mass [COM] acceleration, velocity, and position) that enable deconstruction of the CMVJ into phases, obtain dependent variables, or both (15,18,22,28,37,39). The integration process to obtain COM velocity and position, eg, can become unstable and erroneous when too much noise remains in the GRF data (11). In this case, dependent variables may become compromised and alter important study outcomes. It is impossible to completely remove noise and error while retaining all of the true signal. This means that researchers and practitioners must carefully determine the ideal method to reduce noise in the GRF data at hand.

Applying a low-pass digital filter to raw GRF data is a common procedure used to reduce noise and retain true signal for analysis. The low-pass filter removes frequencies from the raw signal above the designated cutoff while signals below the cutoff frequency are retained. The fourth-order, zero lag (i.e., bidirectional or dual-pass), low-pass Butterworth digital filter is a fairly robust filter often used for biomechanical data (48), especially GRF data recorded during the CMVJ (17,30,34,45). Still, numerous CMVJ studies have analyzed raw GRF data or failed to indicate whether filtered or raw GRF data were analyzed (32,33,37,39,47) despite the possible influence of filtering on study results. In CMVJ studies using a low-pass filter, cutoff frequencies of 10 Hz (46), 12 Hz (24), 16 Hz (5), 17 Hz (30,34), 30 Hz (15), 40 Hz (44,45), and 50 Hz (2,16,18,38) have been reported. Some CMVJ studies provide justification for the selected cutoff frequency, such as plotting the frequency content of the recorded signals and subjectively estimating the primary frequency band (15,16), use of an objective determination method (34,45), or citing its use in a previous study (3,30). However, many studies, including some from the current author(s), provide zero justification for the cutoff frequency selected to reduce noise from the GRF data (14,22,38,46). Inconsistencies relative to filtering, cutoff selection, or both, may be because the filtering process is a combination of art and science requiring an analysis-specific balance between subjective and objective decisions.

There is no clear consensus on the ideal data processing procedures for a CMVJ analysis using GRF data. As such, the purpose of this study was to determine the effect of common filtering procedures on the typical dependent variables studied during CMVJ analyses. The first question was whether dependent variables were affected by using raw or filtered data. We hypothesized that dependent variables from raw data would be greater in magnitude than the same variables from filtered data. The second, follow-up question was whether the various subjective and objective methods to determine the filter cutoff frequency affected the dependent variables differently. We had no strong hypothesis for this question aside from the expectation that differences would be observed among the filter methods.

Methods

Experimental Approach to the Problem

We examined the influence of not filtering GRF data in comparison with filtering the same data with different low-pass filter cutoff frequencies during a CMVJ analysis. Cutoff frequencies were determined using both objective and subjective methods to maintain consistency with contemporary practices. A within-subjects approach was used to identify differences among methods with respect to common dependent variables describing CMVJ performance, power output, and neuromuscular function. Statistical comparisons were conducted using one-way repeated-measures analyses of variance (ANOVAs) supplemented by Cohen's *d* effect sizes (ESs). This study design was selected to provide strength and conditioning professionals with evidence related to whether low-pass filtering procedures are necessary when analyzing the CMVJ using GRF data. Ultimately, this evidence could help ensure that results of CMVJ analyses are as accurate as possible while also maximizing the ability to compare results from different studies.

Subjects

Twenty-two male athletes (mean ± *SD*: 20 ± 2 years [range: 18–23]; 1.99 ± 0.07 m; 93.79 ± 8.48 kg) participated in this study. Subjects were active members of an NCAA Division 1 Basketball program at the time of their testing session. Each subject's testing session was completed within the same 4-hour period (9 AM–1 PM) and before any other organized activities (e.g., strength training, practice, etc.). Subjects were free of any current or previous injury or ailment that would impair their ability to participate in organized basketball activities or perform maximum effort CMVJs. Subjects were informed of the risks and benefits of the protocol and were encouraged to ask questions. The study protocol was approved by the Texas Tech University Review Board (IRB), and written informed consent was obtained in accordance with IRB requirements.

Procedures

During each subject's testing session, age, height, and mass were recorded. Subjects completed identical ∼10-minute, team-specific, dynamic warm-ups supervised by the strength and conditioning staff. Subjects were then provided a demonstration of the CMVJ task followed by up to 5 practice trials to familiarize themselves with performing the movement in the laboratory environment. Then, 3 maximum effort CMVJ trials were recorded while three-dimensional GRF data were obtained using a dual force platform system (OPT 464508; Advanced Mechanical Technology, Inc., Watertown, MA) sampled at 1,000 Hz and interfaced to a PC running Nexus software (version 2.6; Vicon Motion Systems, Ltd., Oxford, United Kingdom). Subjects began each trial standing motionless for ∼1 second with each foot on a force platform. A "go" command was then provided, on which subjects completed 2 consecutive CMVJs while aiming to achieve the greatest jump height as quickly as possible for each jump. Subjects used preferred countermovement depths and arm swings to promote maximum performance (26). Although subjects performed 2 successive maximum-effort CMVJs, only the initial CMVJ was used for variable extraction. Trials were discarded and repeated if the subjects (a) displayed aberrant force production prior to CMVJ initiation (Figure 1), (b) felt as though the trial was not representative of their maximum effort, or (c) were unable to land with each foot contacting its respective takeoff platform before jumping again for the greatest jump height as quickly as possible. Approximately 30 seconds of rest was provided between trials.

Data Processing. Raw GRF data were exported to MATLAB (version R2019a; The Mathworks, Inc., Natick, MA). A total of 6 data filtering methods were used for comparison: raw data, 50 Hz, visual inspection 1, visual inspection 2, 99% signal power 1, and 99% signal power 2. After the data were processed, the dependent variables were calculated with identical procedures. Four of the methods (raw data, 50 Hz, visual inspection 1, and 99% signal power 1) began with a summation of the raw vertical GRF data from the 2 force platforms. For the raw data method, GRF data were not filtered before the dependent variables were calculated. The other 5 methods involved low-pass filtering through a fourth-order, bidirectional (i.e., dual-pass) Butterworth digital filter for which the filter order and the cutoff frequencies were before the 2 passes of the filter. What differed among these methods was how the low-pass cutoff frequency was determined for each trial. For the 50-Hz method, a cutoff frequency of 50 Hz was selected because of its widespread use in CMVJ studies (2,4,16,18,38). The visual inspection 1 method determined the cutoff frequency based on a subjective visual analysis of the signal frequency content. Specifically, the summed GRF signal was padded with trailing zeros, so that the length of the data was

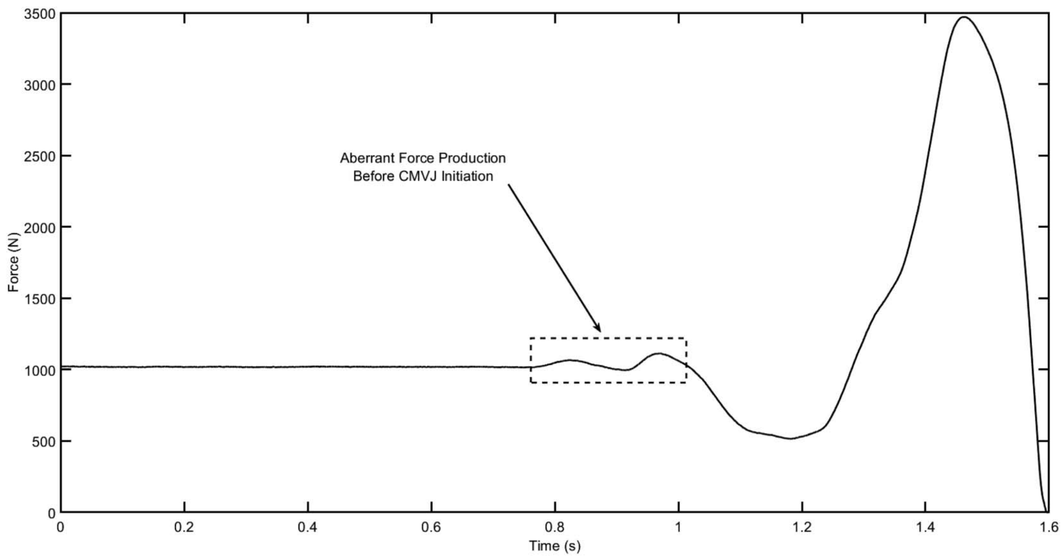

Figure 1. Exemplar vertical ground reaction force vs. time profile with aberrant force production before CMVJ initiation. CMVJ = countermovement vertical jump; trials with aberrant force production similar to that which is depicted in the figure were discarded and repeated.

a power of two. The GRF was then transformed from the time domain to the frequency domain using MATLAB's Fast Fourier Transform function. The frequency content of the summed GRF signal was plotted and subjectively inspected to identify the frequency under which the majority of the signal power (15) was contained (Figure 2A). A similar process was used for the visual inspection 2 method, except cutoff frequencies were determined for the raw vertical GRF data from each platform. Data were then filtered independently and summed together for calculation of dependent variables. It should be noted that the visual inspection 1 and 2 methods return largely subjective results and the selected cutoff frequencies might vary among investigators. Users of these methods should recognize that they require a combination of art and science favoring the former.

For the 99% signal power 1 method, the cutoff frequency was determined from the cumulative power spectrum. Specifically, the summed GRF signal was transformed to the frequency domain as described previously. The cumulative signal power spectrum (43) was then obtained from the single-sided spectrum of the signal. The low-pass cutoff frequency for the Butterworth digital filter was identified as the frequency under which 99% of the signal power was contained (43), as shown in Figure 2B. We chose this method over other objective methods (21,48) for its relative simplicity and expectations of similar cutoff frequency outcomes (43). The 99% signal power 2 method was similar to the 99% signal power 1 method. However, like the visual inspection 2 method, cutoff frequency selection and filtering was performed for each platform's GRF data before summation of the signals. We did not include a filtering method that used a 50-Hz cutoff on the individual platforms' GRF data before summation of the vertical GRF (i.e., a "50 Hz 2" method) as filtering is a linear operation. In other words, filtering raw data from the 2 platforms at 50 Hz and then summing the data together yields the same results as summing the raw data and then filtering at 50 Hz. For each method, the mean cutoff frequency across the 3 trials was calculated for each subject.

The processed vertical GRF data were used to calculate vertical COM acceleration using Newton's law of acceleration ($a = \Sigma F/m$), where "ΣF" represents the vertical GRF minus body weight and "m" represents body mass. Specifically, the average GRF signal from the first 500 data points (i.e., 0.5 seconds) was used to obtain body weight. Body weight was then divided by the absolute value of gravitational acceleration ($9.81\ m \cdot s^{-1} \cdot s^{-1}$) to calculate body mass. Vertical COM velocity and position were calculated as the first and second cumulative time integrals of the vertical COM acceleration, respectively, using the trapezoidal rule. The start of the CMVJ was identified as the time when the vertical GRF was reduced by more than 2.5% of the calculated body weight value (33). Takeoff was identified as the time when the vertical GRF signal decreased below 20 N (15). The GRF time history was then deconstructed into the following phases (15): unloading, eccentric yielding, eccentric braking, and concentric (Figure 3).

Center of mass flight height (i.e., jump height) was calculated as the square of COM vertical velocity at the time of takeoff divided by 2 times the absolute value of gravitational acceleration (35) and presented in units of meters. Center of mass flight height was included because it is the primary metric of CMVJ performance. The modified reactive strength index (RSI_{MOD}) was calculated as the ratio of COM flight height and the time in seconds from the start of the CMVJ to takeoff (i.e., jump time or time to takeoff). Although ratio-based index variables can sometimes coincide with fabricated relationships among dependent variables and make interpretations difficult (1), RSI_{MOD} was calculated because it is considered the best representation of explosiveness during the CMVJ (46). Jump power was calculated according to the mean power equation described by Samozino et al. (41) and reported in units of watts per unit of body weight. Jump power was included as it may be the most practical measure of lower limb power output during jumping (36). The vertical GRF magnitudes at the end of the unloading (unload GRF) and eccentric braking (braking GRF) phases were extracted and normalized to the percentage of body weight unloaded and multiples of body weight, respectively. These variables were included because the unload GRF is significantly correlated with CMVJ performance (3) and the braking GRF represents the stored elastic strain energy

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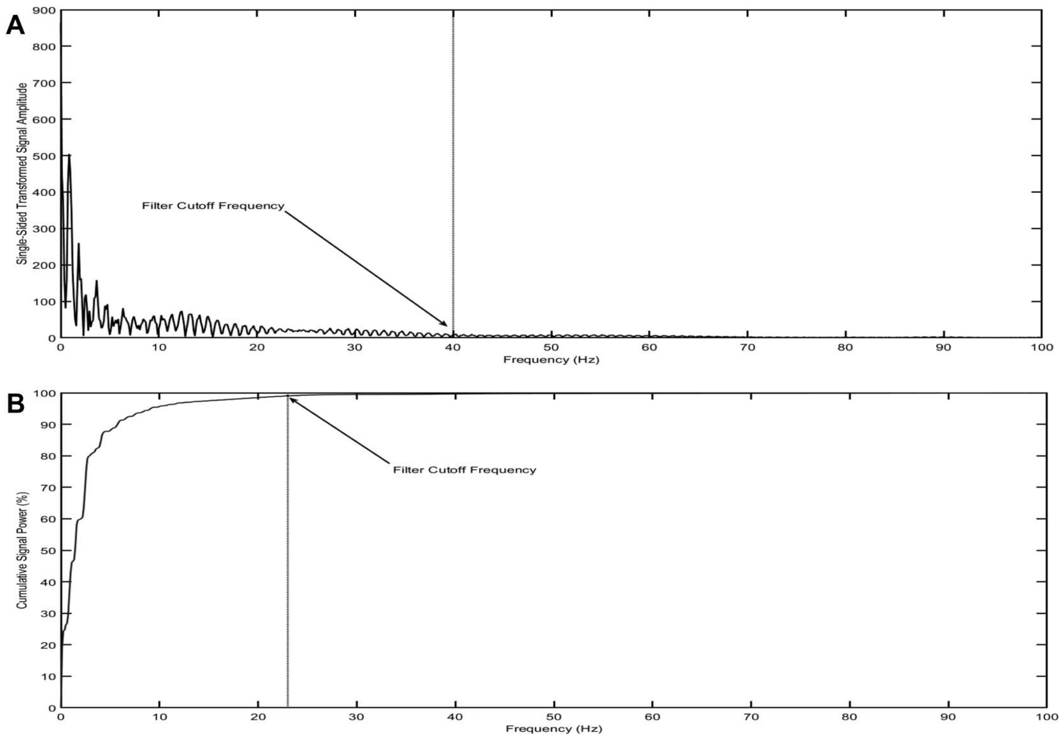

Figure 2. Exemplar representation of the low-pass filter cutoff frequency identification processes using (A) visual inspection of the Signal's primary frequency band and (B) 99% of the cumulative signal power.

in the system (6) that sets the foundation for concentric mechanical output (16). The vertical yank (27), sometimes called rate of force development, during the unloading, eccentric yielding, and eccentric braking phases was determined as the difference in the vertical GRF magnitudes at the start and end of each phase divided by the time in seconds between the 2 magnitudes and presented in units of body weights per second. These yank values were included for 2 reasons. First, yank is commonly studied in the literature (3,25,32,39). Second, combining CMVJ performance metrics with yank values for the described phases can reveal whether an athlete can take advantage of rapid force production, or overcome slow force production, throughout critical periods of the stretch-shortening cycle (15). Countermovement depth was calculated as the change of COM position between the start of unloading and the end of eccentric braking and presented in units of meters. Countermovement depth was

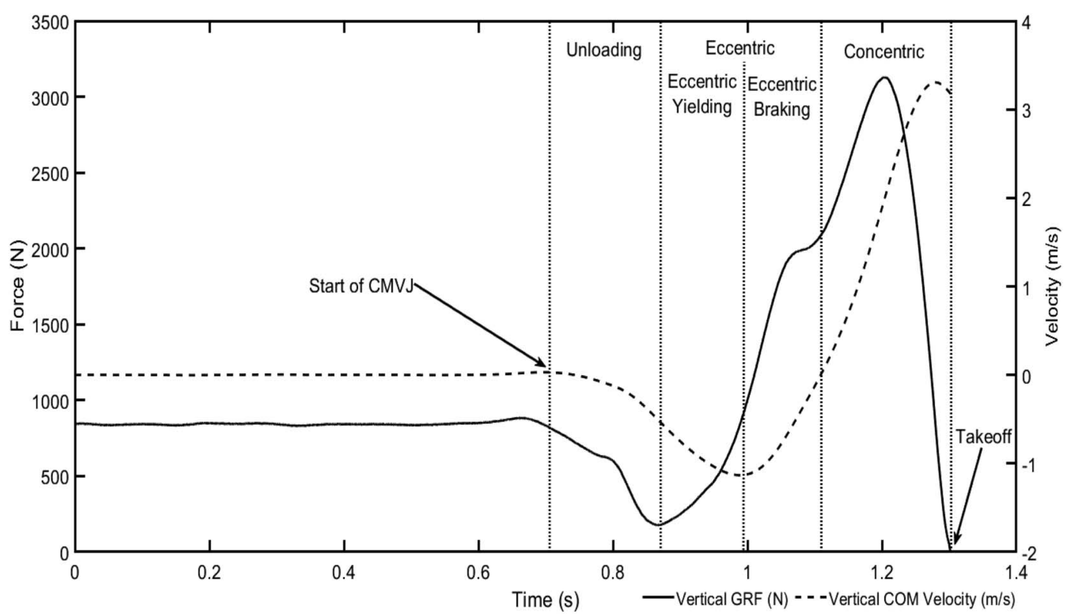

Figure 3. Exemplar representation of the CMVJ phases defined by the vertical GRF and COM velocity curves. CMVJ = countermovement vertical jump; GRF = ground reaction force; COM = center of mass.

included because greater depths tend to produce greater COM flight heights (42), meaning it can reveal kinematic movement strategies among athletes that can partially dictate performance differences. Push-off distance was calculated as the difference in COM position between the end of eccentric braking and takeoff and presented in units of meters. This variable was included because it can influence outcomes of CMVJ tests if it is not accounted for or controlled in comparisons among athletes who have different lower extremity segment lengths (36).

Statistical Analyses

During data collection, one subject began to step off the platforms before termination of each recorded trial. This significantly affected the frequency content of the recorded data. For instance, the visual inspection 1 and 2 methods for this subject determined cutoff frequencies greater than 150 Hz, which was more than twice the ~61- to 67-Hz cutoff determined for the remaining subjects with those methods. Although the trials could have been manually trimmed to remove the stepping off action at the end of the trials, we chose to avoid manipulating any trial prior to processing. Therefore, this subject's data were removed, resulting in a final sample of 21 subjects (20 ± 2 years; 1.99 ± 0.07 m; 93.56 ± 8.62 kg).

Processed data were exported to SPSS software (IBM, Corp., Armonk, NY), where one-way repeated-measures ANOVAs were used to determine whether differences among filtering methods were statistically significant. Data normality was assessed visually using histograms, and Mauchly's test was used for the assumption of sphericity. If normality or sphericity was violated, the Huynh-Feldt correction was used to obtain omnibus statistical probability values. The a priori probability level for statistical significance was set at 5% (i.e., $\alpha = 0.05$). In the event of a significant omnibus ANOVA test, the Šidák adjustment was used to interpret pairwise comparisons. Cohen's *d* ES values were calculated (7) to supplement the statistical probabilities for the pairwise comparisons. Effect size values were interpreted using Hopkin's (20) scale ($0.0 <$ trivial ≤ 0.2 small $< 0.6 \leq$ moderate $< 1.2 <$ large $\leq 2.0 <$ very large). The coefficient of variation (CV) was calculated to determine the variation among subjects for each method, and the CV values were averaged across methods and provided alongside the range of CV values to demonstrate the relative reliability across methods.

Results

The group mean ± *SD* (where appropriate) values calculated across the subject mean cutoff frequencies for each method were raw data: N/A; 50 Hz: 50 ± 0 Hz, visual inspection 1: 61.11 ± 7.17 Hz, visual inspection 2: 67.42 ± 17.84 Hz, 99% signal power 1: 18.75 ± 7.17 Hz; 99% signal power 2: 23.11 ± 9.82 Hz. Descriptive data for the dependent variables are presented as the mean ± *SD* across subjects for each method, with 95% confidence intervals also provided (Tables 1–3). The small ranges of CV values indicated that the variables were reliable across methods (Tables 1–3).

The omnibus ANOVA tests identified a significant difference among methods for the following variables: COM flight height, RSI_{MOD}, jump power, push-off distance, and concentric time ($p < 0.01$ for all variables). For COM flight height (Table 1), pairwise comparisons revealed significantly greater heights for raw data, visual inspection 2, and visual inspection 1 vs. 99% signal power 2 (p values ≤ 0.04; ES values: 0.14–0.29). Center of mass flight height was also significantly higher for raw data, visual inspection 2 and 50 Hz vs. 99% signal power 1 (p values < 0.01; ES values ≥ 0.23–0.33). All other pairwise comparisons were neither statistically significant nor greater than a small or trivial effect size. For RSI_{MOD} (Table 1), pairwise comparisons suggested significantly greater explosiveness for raw data and visual inspection 2 than 99% signal power 1 (p values ≤ 0.05, ES values: 0.15–0.18). For jump power (Table 1), pairwise comparisons revealed significantly greater power for raw data and visual inspection 2 vs. 99% signal power 1 (p values < 0.01; ES values: 0.35–0.48). Jump power was also significantly greater for raw data, visual inspection 2, and visual inspection 1 vs. 99% signal power 2 (p values ≤ 0.04, ES values: 0.23–0.41).

For push-off distance (Table 1), pairwise comparisons suggested significantly shorter distances for raw data, visual inspection 1, and visual inspection 2 vs. 99% signal power 1 and 2 (p values ≤ 0.04, ES values: 0.25–0.50). For concentric time (Table 2), pairwise comparisons revealed the same pattern of results as push-off distance, with significantly shorter times for raw data, visual inspection 1, and visual inspection 2 vs. 99% signal power 1 and 2 (p values ≤ 0.04, ES values: 0.08–0.16). The omnibus ANOVA tests were not statistically significant (p values > 0.05) for all other dependent variables (Tables 1–3).

Discussion

The purpose of this study was to examine the effects of analyzing unfiltered GRF data in comparison with filtered data using different low-pass filter cutoff frequencies during a CMVJ analysis. The main results of this study are that both the choice to apply a low-pass filter or use the raw data and the specific filter cutoff frequency selected affects the results of CMVJ analyses. Specifically, the following variables were sensitive to the different filtering procedures: COM flight height, RSI_{MOD}, jump power, push-off distance, and concentric time. These results partially support our first hypothesis that dependent variables from raw data would be greater in magnitude than the same variables from filtered data. We did not have a strong hypothesis for whether the various subjective and objective methods to determine the filter cutoff frequency affected the dependent variables differently. Still, the results suggest low-pass filtering methods do affect dependent variables in a CMVJ analysis. Briefly, this study revealed 2 main results. First, CMVJ analyses of GRF data using the current dependent variables do not need to use low-pass filtering on the recorded data, although the 50-Hz method may be a suitable secondary option. Second, strength and conditioning professionals should cautiously interpret results of previous work in which low-pass filtering or different low-pass filtering procedures to their own were used.

A face-value explanation for the sensitivity of COM flight height, RSI_{MOD}, and jump power to specific filter methods might be that inappropriate data smoothing techniques, or a lack thereof, can fail to reduce noise and measurement errors before integration computations, similar to what can occur with derivative computations from motion capture data (10,19). However, it is important to note that the signal power 1 and 2 methods, which objectively selected the cutoff frequencies using an evidence-based process, produced significantly greater push-off distances and longer concentric phase durations than most of the other methods. This is because signal power 1 and 2 identified the time of takeoff later in the force-time curve when compared with

Table 1

Results for all CMVJ performance and kinematic variables when processed using different filtering methods.*

Variable	99% signal power 1 Mean + *SD* (95% CI)	99% signal power 2 Mean + *SD* (95% CI)	50 Hz Mean + *SD* (95% CI)	Visual inspection 1 Mean + *SD* (95% CI)	Visual inspection 2 Mean + *SD* (95% CI)	Raw data Mean + *SD* (95% CI)	Reliability CV (range)
COM flight height (m)	0.439 ± 0.053 (0.413 to 465)	0.441 ± 0.056 (0.413 to 0.469)	0.448 ± 0.057 (0.420 to 0.476)^{SP1}	0.449 ± 0.057 (0.421 to 0.477)^{SP2}	0.451 ± 0.055 (0.424 to 0.478)$^{SP1,\ SP2}$	0.456 ± 0.052 (0.430 to 0.482)$^{SP1,\ SP2}$	12.29 (11.40–12.27)
RSI_{MOD}	0.527 ± 0.124 (0.466 to 0.588)	0.529 ± 0.127 (0.466 to 0.592)	0.542 ± 0.137 (0.474 to 0.610)	0.542 ± 0.137 (0.474 to 0.610)^{SP2}	0.546 ± 0.136 (0.479 to 0.613)$^{SP1,\ SP2}$	0.550 ± 0.137 (0.482 to 0.618)$^{SP1,\ SP2}$	24.64 (23.52–25.27)
Jump power ($W \cdot BW^{-1}$)	2.924 ± 0.382 (2.736 to 3.112)	2.942 ± 0.411 (2.739 to 3.145)	3.036 ± 0.446 (2.816 to 3.256)	3.037 ± 0.444 (2.818 to 3.256)^{SP2}	3.063 ± 0.423 (2.854 to 3.272)$^{SP1,\ SP2}$	3.106 ± 0.400 (2.909 to 3.303)$^{SP1,\ SP2}$	13.83 (12.87–14.69)
CM depth (m)	−0.275 ± 0.048 (−0.299 to −0.251)	−0.275 ± 0.048 (−0.299 to −0.251)	−0.275 ± 0.048 (−0.299 to −0.251)	−0.275 ± 0.048 (−0.299 to −0.251)	−0.275 ± 0.048 (−0.299 to −0.251)	−0.275 ± 0.048 (−0.299 to −0.251)	17.45 (17.45–17.45)
Push-off dist. (m)	0.449 ± 0.049 (0.429 to 0.469)$^{VI2,\ RD}$	0.447 ± 0.040 (0.457 to 0.497)$^{VI2,\ RD}$	0.437 ± 0.044 (0.415 to 0.459)	0.437 ± 0.044 (0.415 to 0.459)	0.434 ± 0.043 (0.413 to 0.455)	0.429 ± 0.042 (0.408 to 0.450)	9.94 (8.94–10.91)

*Mean = mean across subjects; CMVJ = countermovement vertical jump; 95% CI = 95% confidence interval band; COM = center of mass; BW = body weight; CV = average coefficient of variation across methods (%); Range = range of CV values; when present, SP1 = significantly greater than signal power 1 ($p < 0.05$); VI1 = significantly greater than visual inspection 1 ($p < 0.05$); 50Hz1 = significantly greater than 50 Hz 1 ($p < 0.05$); SP2 = significantly greater than signal power 2 ($p < 0.05$); VI2 = significantly greater than visual inspection 2 ($p < 0.05$); RD = significantly greater than raw data ($p < 0.05$).

Table 2

Durations of the CMVJ and the CMVJ phases when processed using different filtering methods.*

Variable	99% signal power 1 Mean + *SD* (95% CI)	99% signal power 2 Mean + *SD* (95% CI)	50 Hz Mean + *SD* (95% CI)	Visual inspection 1 Mean + *SD* (95% CI)	Visual inspection 2 Mean + *SD* (95% CI)	Raw data Mean + *SD* (95% CI)	Reliability CV (range)
Jump time	0.876 ± 0.176 (0.789–0.963)	0.876 ± 0.175 (0.790–0.962)	0.872 ± 0.176 (0.785–0.959)	0.872 ± 0.176 (0.785–0.959)	0.871 ± 0.176 (0.784–0.958)	0.881 ± 0.184 (0.790–0.972)	20.25 (19.97–20.88)
Unload time	0.302 ± 0.197 (0.204–0.399)	0.302 ± 0.196 (0.205–0.399)	0.302 ± 0.198 (0.203–0.399)	0.301 ± 0.198 (0.203–0.399)	0.300 ± 0.199 (0.202–0.398)	0.312 ± 0.199 (0.214–0.410)	64.65 (61.87–66.33)
Yielding time	0.138 ± 0.037 (0.120–0.156)	0.138 ± 0.037 (0.120–0.156)	0.140 ± 0.038 (0.121–0.159)	0.140 ± 0.038 (0.121–0.159)	0.140 ± 0.038 (0.121–0.159)	0.140 ± 0.038 (0.121–0.159)	27.03 (26.81–27.14)
Braking time	0.172 ± 0.037 (0.154–0.190)	0.173 ± 0.037 (0.155–0.191)	0.172 ± 0.037 (0.154–0.190)	0.172 ± 0.037 (0.154–0.190)	0.172 ± 0.037 (0.154–0.190)	0.172 ± 0.037 (0.154–0.190)	21.49 (21.38–21.51)
Concentric time	0.264 ± 0.045 (0.242–0.286)$^{VI1,\ VI2,\ RD}$	0.263 ± 0.044 (0.241–0.285)$^{VI1,\ VI2,\ RD}$	0.259 ± 0.045 (0.237–0.281)	0.259 ± 0.045 (0.237–0.281)	0.258 ± 0.045 (0.236–0.280)	0.257 ± 0.046 (0.234–0.280)	17.31 (16.73–17.89)

*Unit of measure for all variables: seconds; CMVJ = countermovement vertical jump; CI = confidence interval; Mean = mean across subjects; CV = average coefficient of variation across methods (%); Range = range of CV values; when present, SP1 = significantly greater than signal power 1 ($p < 0.05$); VI1 = significantly greater than visual inspection 1 ($p < 0.05$); 50Hz1 = significantly greater than 50 Hz 1 ($p < 0.05$); SP2 = significantly greater than signal power 2 ($p < 0.05$); VI2 = significantly greater than visual inspection 2 ($p < 0.05$); RD = significantly greater than raw data ($p < 0.05$).

Table 3
Vertical GRF and yank variables when processed using different filtering methods.*

Variable	99% signal power 1 Mean ± SD (95% CI)	99% signal power 2 Mean ± SD (95% CI)	50 Hz Mean ± SD (95% CI)	Visual inspection 1 Mean ± SD (95% CI)	Visual inspection 2 Mean ± SD (95% CI)	Raw data Mean ± SD (95% CI)	Reliability CV (range)
Unload GRF (% BW)	0.648 ± 0.137 (0.580 to 0.716)	0.649 ± 0.137 (0.581 to 0.717)	0.651 ± 0.136 (0.584 to 0.718)	0.651 ± 0.136 (0.584 to 0.718)	0.651 ± 0.136 (0.584 to 0.718)	0.651 ± 0.136 (0.584 to 0.718)	20.43 (20.08–21.14)
Braking GRF (× BW)	2.139 ± 0.328 (1.974 to 2.304)	2.138 ± 0.332 (1.974 to 2.302)	2.136 ± 0.328 (1.974 to 2.298)	2.136 ± 0.328 (1.974 to 2.298)	2.136 ± 0.328 (1.974 to 2.298)	2.137 ± 0.328 (1.975 to 2.299)	15.38 (15.33–15.55)
Unload yank ($BW\cdot s^{-1}$)	−3.224 ± 2.004 (−4.212 to −2.236)	−3.222 ± 1.993 (−4.205 to −2.239)	−3.285 ± 2.068 (−4.305 to −2.265)	−3.285 ± 2.068 (−4.350 to −2.265)	−3.293 ± 2.083 (−4.320 to −2.266)	−3.270 ± 2.102 (−4.307 to −2.233)	62.91 (61.85–64.28)
Yielding yank ($BW\cdot s^{-1}$)	5.521 ± 2.412 (4.273 to 6.561)	5.497 ± 2.322 (4.352 to 6.642)	5.434 ± 2.343 (4.278 to 6.590)	5.442 ± 2.377 (4.270 to 6.614)	5.437 ± 2.375 (4.266 to 6.608)	5.417 ± 2.320 (4.273 to 6.561)	43.20 (42.24–43.68)
Braking yank ($BW\cdot s^{-1}$)	7.230 ± 3.802 (5.355 to 9.105)	7.235 ± 3.797 (5.362 to 9.108)	7.239 ± 3.798 (5.366 to 9.112)	7.240 ± 3.798 (5.367 to 9.113)	7.240 ± 3.798 (5.367 to 9.113)	7.244 ± 3.796 (5.372 to 9.116)	52.47 (52.40–52.58)

*Mean = mean across subjects; 95% CI = 95% confidence interval band; GRF = ground reaction force; BW = body weight; CV = average coefficient of variation across methods (%); Range = range of CV values; when present, SP1 = significantly greater than signal power 1 ($p < 0.05$); VI1 = significantly greater than visual inspection 1 ($p < 0.05$); 50Hz1 = significantly greater than 50 Hz 1 ($p < 0.05$); SP2 = significantly greater than signal power 2 ($p < 0.05$); VI2 = significantly greater than visual inspection 2 ($p < 0.05$); RD = significantly greater than raw data ($p < 0.05$).

the other methods. We presume this is because the aggressiveness of the cutoff frequencies made it difficult for the filter to adequately handle the steep slope of the GRF curve before takeoff, which causes a ringing artifact in the data (Figure 4). This ringing artifact is similar to what occurs when applying a low-pass filter to a square wave type of signal (40). Ultimately, the delayed time of takeoff altered the COM flight height, RSI_{MOD}, and jump power variables as smaller takeoff velocity magnitudes were extracted because the COM vertical velocity reaches its peak and then decreases before takeoff (23) as shown in Figure 2. Use of a low-pass filter with an objectively determined cutoff frequency may be considered "best practice" when analyzing recorded data most biomechanics-based analyses. However, these results suggest the procedure might be poorly suited for CMVJ analyses of GRF data in which the time of takeoff is central to dependent variable calculations.

In addition to the significant filter-related differences in COM flight height, RSI_{MOD}, and jump power, the nonstatistically significant differences among methods for jump time and unload time should not be overlooked. For instance, the raw data method produced an average unload time that was ~0.010–0.012 seconds longer than all the filter methods. Despite a lack of statistical significance for this variable, the difference may warrant further study because the magnitude of the difference is equal to ~5% of the typical unloading phase duration (15,18). Speculatively, this difference may be because noise-related fluctuations in the GRF signal during the quiet standing period were not reduced in the raw data method. As a result, the raw data GRF curve may tend to exceed the predefined threshold for the start of the CMVJ (33) sooner than the filtering methods. Obviously, earlier detection of CMVJ initiation using raw data vs. filtered data could be dependent on a combination of the integrity of force platforms components used to record data, the permitted CMVJ initiation techniques (e.g., arm swing, initial upward COM movements), and effects of the specific filter process. For this reason, use of the 50 Hz method may be suitable as it can reduce noise-related fluctuations during quiet standing without altering dependent variables in comparison with the raw data method. It is therefore recommended that each analysis be preceded by inspection of the fluctuations in the recorded GRF curves during the quiet standing period. From that inspection, an educated decision can be made to determine whether filtering is needed to identify CMVJ initiation.

Another key result was that none of the vertical GRF or yank magnitudes were different among the various filtering procedures. This is important because certain vertical GRF and yank magnitudes can reveal neuromuscular function and rapid force production abilities (12,31) that translate to function in competitive sport environments. Importantly, researchers and practitioners conducting CMVJ tests where only discrete GRF or phase-specific yank results are considered might not need to be concerned with whether raw or filtered GRF data should be used for analysis. It may be surprising that the tested filter methods did not affect the unload yank because the generally longer unload time in the raw data method could be expected to decrease the unload yank magnitude. This could mean that potential differences among filter methods for identifying the start of the CMVJ are vital considerations only for researchers needing to maintain methodological consistency and not for practitioners conducting jump tests with small sport-specific athlete populations. Importantly, the ability to conduct a CMVJ analysis of vertical GRF magnitudes, yank magnitudes, or both, using raw data could simplify the demands placed on the user during data analysis, making analyses of raw GRF data more attractive to researchers

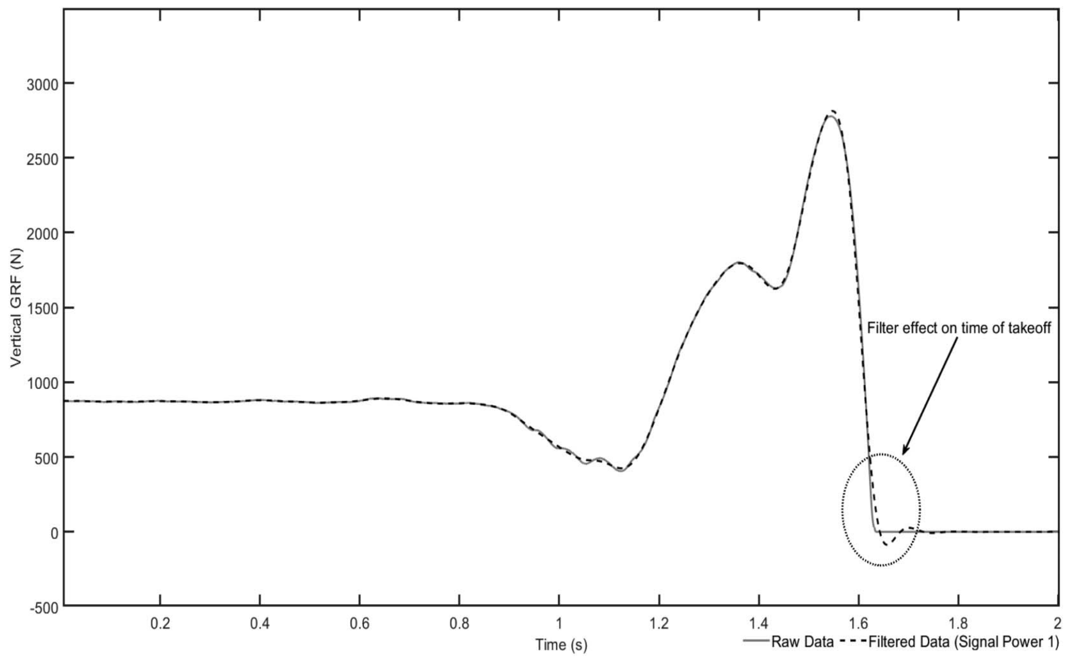

Figure 4. Exemplar representation of a low-pass Filter's effect on the time of takeoff during the CMVJ. CMVJ = countermovement vertical jump; GRF: ground reaction force; the graphic represents the time between the first recorded data point and 50% of the flight phase.

and practitioners. Although this interpretation may only relate to the variables examined herein, we have no reason to believe that other discrete GRF (e.g., peak concentric vertical GRF (17)) or phase-specific yank (e.g., concentric slope (3)) variables would be negatively impacted by analyzing raw vs. objectively filtered GRF data. This presumes that all variables do not require a GRF magnitude at the time of takeoff, since those magnitudes should differ between raw vs. objectively filtered GRF data.

Determining whether raw or filtered data should be used in a CMVJ analysis should always be made according to the data recorded because the signal content will be unique to the force platform instruments used and the recording environment (e.g., laboratory, practitioner setting, etc.). Based on the current data and recording environment, which we presume would be similar to other laboratory settings, use of raw data appears ideal. This is because the identified time of takeoff appears to best represent the true start of the flight phase and the corresponding performance variables (COM flight height, RSI_{MOD}, and jump power) are sensitive to this event in time. Moreover, the discrete GRF and yank variables were consistent across all filter processes, further supporting use of raw data. However, the use of raw data might present challenges with respect to detecting the start of a CMVJ (i.e., countermovement initiation) for the reasons described previously. In recording environments where particularly noisy force platforms are used or the subjects display noticeable, albeit acceptable, GRF fluctuations during quiet standing, filtering the raw GRF data using a fourth-order, bidirectional, low-pass filter with a 50-Hz cutoff frequency may be required. This process should attenuate potentially influential GRF fluctuations without altering key dependent variables. Furthermore, we do not recommend the visual inspection methods because their subjective nature would likely cause too much variability in cutoff frequencies determined by different investigators, even for the same GRF data set. The decision to filter the GRF data should, ultimately, be carefully determined by the researcher or practitioner conducting the CMVJ test according to the research question and targeted dependent variables. Rationale supporting the choice to either analyze raw data or filtered data should be provided regardless of the procedure selected.

Researchers and practitioners who elect to filter GRF data before analysis should be aware of 2 unintended consequences of the dual-pass (i.e., bidirectional) filter. First, although the dual-pass filter prevents lag in the data that would otherwise occur with a single pass, the dual-pass doubles the order of the filter. This means a fourth-order dual-pass filter (as used herein) is effectively an eighth-order filter. Increasing the order of the filter can return a larger ringing artifact in the data near sharp transitions like what was discussed previously regarding the time of takeoff. Second, the dual-pass filter decreases the cutoff frequency by a factor of 1.2465 (40). This means that the current 50-Hz method, for example, was effectively a 40.11-Hz filter. We are not aware of any published CMVJ studies that, when GRF data were filtered, specified whether the reported order and cutoff frequency of the filter were before or after the 2 passes. Accordingly, future studies examining filtered GRF data should indicate whether the reported cutoff frequency and order of the filter are before or after the 2 passes in addition to providing rationale supporting the choice to filter (or not filter) the data.

Practical Applications

Strength and conditioning professionals conducting CMVJ tests must be aware of both the effects that analyzing raw vs. filtered GRF data can produce and the effects of different filter cutoff frequencies on CMVJ test results. The choice to analyze filtered vs. raw data can alter dependent variables by delaying the identified time of takeoff. However, discrete GRF and phase-specific yank magnitudes are not sensitive to low-pass filtering. Therefore, we recommend that CMVJ analyses using GRF data be performed on raw data or on processed data using the current 50-Hz filtering method. This study provides strength and conditioning researchers and practitioners with information that, when considered, can help improve the integrity of future CMVJ analyses, comparisons among various studies' results, or both.

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