

Objective classification of countermovement jump force-time curve modality: within athlete-consistency and associations with jump performance

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Abstract

Force-time curves produced during a countermovement jump (CMJ) have traditionally been classified by visual observation as either unimodal (one concentric phase peak) or bimodal (two peaks). The association between CMJ modality and jump performance remains unclear and future studies may benefit from standardising and expanding modality classification. This study described a numerical method based on the timing and relative magnitude of concentric force-time curve prominences. Adult male elite rugby union players ($n = 214$) performed six CMJs on a force-instrumented treadmill and an algorithm using turning-point logic was applied to categorise jumps and define modality sub-groups. A sensitivity analysis demonstrated that the minimum prominence threshold (MPT) affected categorisation, as the proportion of bimodal jumps decreased with each 1% increase in MPT. Within-athlete consistency was also affected; between 43% and 63% of participants were consistently categorised as bimodal or unimodal depending on the selected MPT. Modified reactive strength index (RSImod), but not jump height or take-off momentum, was greater in unimodal jumps. Take-off momentum and RSImod were greater in subcategories where maximum force occurred early in the concentric phase. Future research should implement objective classification methods to enhance transparency and comparability and consider subcategories to investigate CMJ force production strategies.

Keywords: Bimodal; countermovement jump; ground reaction force; jumping; performance

Introduction

Countermovement jump (CMJ) performance is a reliable and useful measure of lower body power (Markovic et al., 2004). The measurement of the ground reaction force during the CMJ has become popular as it provides additional objective information that is used to monitor athletic ability, adaptation to training and neuromuscular fatigue (Claudino et al., 2017; Cormie et al., 2009). In addition to discrete measures derived from the ground reaction force data, it has been recommended to examine the entire force-time curve (Chavda et al., 2018; Guess et al., 2020; Krzyszkowski et al., 2020; McHugh et al., 2021). In doing so, two different shapes of the force-time curve during the concentric phase have been observed: unimodal (a single vertical force peak) and bimodal (two distinct vertical force peaks). At least half of jumpers have been classified as bimodal in competitive athletes and physically active students (Kennedy & Drake, 2017; Lake & McMahon, 2018; McHugh et al., 2021; Peng et al., 2019).

Subcategories of these two modalities have also been described, based on the relative magnitude of the two peaks in a bimodal curve (McHugh et al., 2021).

The practical relevance of these different force-time curve shapes is unclear as there is inconsistent evidence for the relationship between CMJ performance and curve categorisation. For example, some authors propose that the bimodal curve is associated with enhanced jump performance (Cormie et al., 2009; Peng et al., 2019), while others suggest that it represents inefficient utilisation of the stretch shortening cycle (Kennedy & Drake, 2018). It has also been proposed that the timing of peak force production determines whether or not the force-time curve is optimal, regardless of modality (McHugh et al., 2021). One notable limitation of published studies to date is that the jumps were classified as unimodal or bimodal subjectively by visual inspection of the force-time curve. The lack of an objective criterion limits comparison across studies and therefore convincing insights into the practical relevance of force-time curves.

Another reason for the conflicting evidence about the performance implications of CMJ modality may be that the unimodal and bimodal categories encompass so many force-time curve variations that they are too broad to be meaningful, since clustering of dissimilar curves within these categories may wash out important differences (McHugh et al., 2021). Understanding the practical relevance of force-time curve modality is further limited by methodological shortcomings. For instance, most studies in this field include relatively small samples which limits the statistical power required to provide strong evidence and should therefore be interpreted with caution. Future CMJ studies may therefore benefit from improved methodologies for categorising force-time curves objectively, in sub-groups specific enough to improve the sensitivity of the analysis and with greater efficiency to enable more convenient automated analysis of larger samples.

In addition to modality differences between athletes, studies have reported that some individuals produce both unimodal and bimodal patterns within a single testing session (Lake & McMahon, 2018; Peng et al., 2019). It is important to consider within-athlete consistency when classifying athletes into a force-time curve category to avoid misclassification if this information is intended to be used to prescribe training and/or monitor athlete performance. In a group of 15 male collegiate athletes, 80% was found to be consistent (two athletes unimodal, ten athletes bimodal) across three CMJ trials, but this figure was reduced to 60% (all bimodal) after completing 10 trials (Lake & McMahon, 2018). Subsequent research has sometimes limited inclusion to participants that demonstrate consistent modality across three trials (Peng et al., 2019), and it was recommended that practitioners consider athletes on an individual basis when investigating CMJ strategy (Lake & McMahon, 2018). Nevertheless, these findings may also be sensitive to the inherent subjectivity in visual inspection methods of classification as there is currently no data available on intra- and inter-rater reliability. Moreover, even a standardised objective definition of CMJ bimodality would need to be tuned in such a way as to avoid being either insensitive or overly sensitive to a bimodal shape within the force-time curve. This means that any new numerical classification approach should also undergo sensitivity analysis to illustrate how the tuning values affect classification results.

In this study, we describe a novel, objective method for categorisation of force-time curves to (i) show the influence of varying classification thresholds on the proportionate categorisation of jumps, (ii) assess within-athlete consistency of CMJ force-time curves, and (iii) compare CMJ performance between force-time curve categories. We hypothesised that increasing the threshold would result in a decrease in the proportion of bimodal jumps and an increase in the

number of participants that consistently demonstrated a unimodal/bimodal curve across all jumps. Finally, we hypothesised that jump performance measures would not differ between unimodal and bimodal jumps but that subcategories featuring a force peak in the early part of the concentric phase would be associated with better CMJ performance.

Materials and methods

Sampling and recruitment

The entire population of male elite provincial rugby union players in the local province were invited to participate in the study. Participants were eligible if they were medically fit to participate in competitions and had not suffered a lower limb injury less than 6 months before testing. The study received approval from the XXX University Human Research Ethics Committee before commencement (REF: XXX) and 214 players provided written informed consent to participate.

Data collection

The data collection was conducted in a controlled environment in an indoor biomechanics laboratory. Prior to testing, participants performed a standardised ten-minute warm-up routine involving dynamic stretching, running drills and sub-maximal jumps. They then performed six vertical CMJs (hands on hips) on a research-grade floor-level force-instrumented treadmill (Bertec Corporation, USA). The treadmill was used out of convenience and provided a stable jumping surface with comparable force signal fidelity to a floor-embedded plate. It was bolted to a mounting plate that had been permanently fixed to the floor by the manufacturer using epoxy. The belts were also actively locked in place using the treadmill motors. Participants were instructed to stand still for up to 3 s, and then given the cue to ‘jump as high as possible’. To reduce potential fatigue effects, the CMJs were executed in three sets of two jumps with participants resting in quiet standing for 20 s between jumps and for 2 min between sets. Measurements of the vertical ground reaction force were taken at 3000 Hz during each CMJ by the instrumented treadmill using a commercial data acquisition software package (MyoResearch 3.14, Noraxon, USA).

Data processing

Phase segmentation, feature extraction and modality analysis were performed for each CMJ using a custom Matlab script (R2019b, Mathworks Inc, USA). Take-off and landing events were detected using standard force onset and offset detection with a threshold of 20 N. Participant body weight was estimated from the average force during a 1 s quiet standing interval detected before take-off. Jump initiation was defined as the first sustained recession of the vertical force below 95% of body weight after quiet standing. Impulse-momentum calculations were used to estimate body centre of mass velocity and position over time. However, due to slight occasional force perturbations prior to initiation caused by postural sway or pre-loading, centre of mass position and velocity were initialised to zero at the last quiet standing interval preceding initiation rather than from initiation. As jump height is the main performance outcome measure of a CMJ, we selected variables that incorporate this measure to address the third aim of the study, namely, jump height, modified reactive strength index (RSI_{mod}) and take-off momentum. Jump height was calculated from take-off velocity and RSI_{mod} was calculated as jump height divided by time from initiation to take-off (Ebben

& Petushek, 2010), and take-off momentum was calculated as take-off velocity multiplied by body mass (McMahon et al., 2020).

Objective method for classification of jumps

The modality classification was conducted on the concentric phase portion of the force-time curves for each jump, beginning at the point on the curve representing zero velocity (F_{z0}), which is also the lowest position of the centre of mass. The algorithm used turning-point logic to classify the curve as bimodal if it could find two peaks (F_{z1} and F_{z3}) that both exceeded a minimum prominence threshold (MPT) relative to the minimum value (F_{z2}) between them (Figure 1(a)). Therefore, curves were classified as unimodal if only one peak was found during the concentric phase, or if either prominence test failed, i.e., $(F_{z1} - F_{z2})/F_{z2} < \text{MPT}$ or if $(F_{z3} - F_{z2})/F_{z2} < \text{MPT}$.

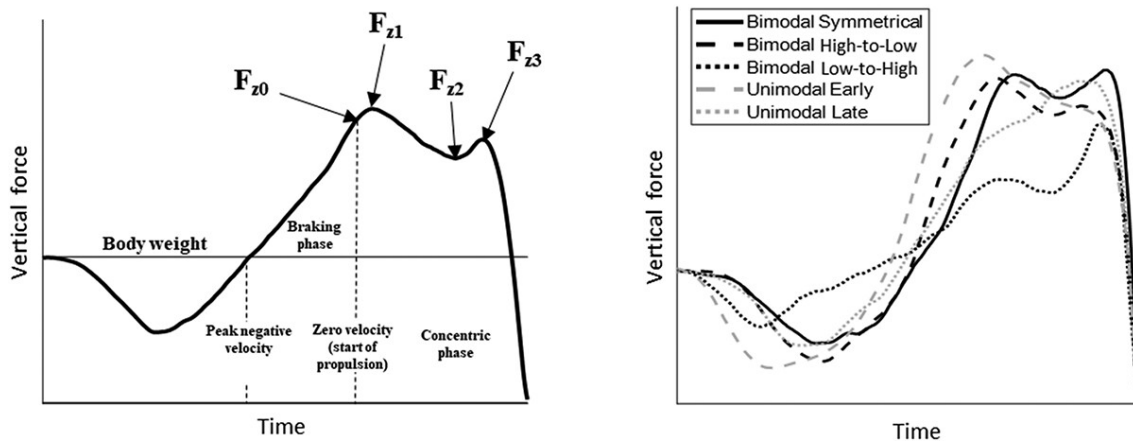


Figure 1. Illustration of the counter movement jump modality features extracted from the force-time curve (left) and examples of the different subcategories (right).

In addition, we subcategorised jumps based on the relative size of the bimodal peaks and the timing of the unimodal peaks. Bimodal curves were thus sub-classified as High-to-Low if the first peak was higher, i.e., $(F_{z1} - F_{z3})/F_{z1} > \text{MPT}$, Low-to-High if it was lower $(F_{z3} - F_{z1})/F_{z3} > \text{MPT}$ or symmetrical if similar (Figure 1(b)). Unimodal curves were sub-classified as early or late based on whether the single peak (F_{z1}) occurred in the first or second half of the concentric phase, respectively (Figure 1(b)).

Data analysis

To address the first aim of the study, all jumps ($n = 1284$) were categorised as either bimodal (and High-to-Low, Low-to-High or Symmetrical subcategories) or unimodal (and Early or Late subcategories). A sensitivity analysis on the proportion of jumps in each category was conducted by repeating the categorisation process with minimum prominence thresholds of 0% (MPT_0), 1% (MPT_1), ... 20% (MPT_{20}). We analysed the modality prevalence for all the thresholds that produced some bimodal curves to provide insight into the range of prominences in the dataset (the results showed that no bimodal curves were detected above MPT_{20} , in other words, the largest difference between both peaks and the nadir between the peaks across all jumps was 20%).

Within-athlete consistency was investigated by assessing the categorisation of each of the six jumps performed by each participant. In the absence of a true definition of bimodality, we only analysed within-athlete modality consistency for minimum prominence thresholds of 0% to 5%, which we considered to be a range that may be visually ambiguous when performing subjective categorisation of curve modality (Figure 2). The aim was to demonstrate the potential effect of subjective classification in these cases.

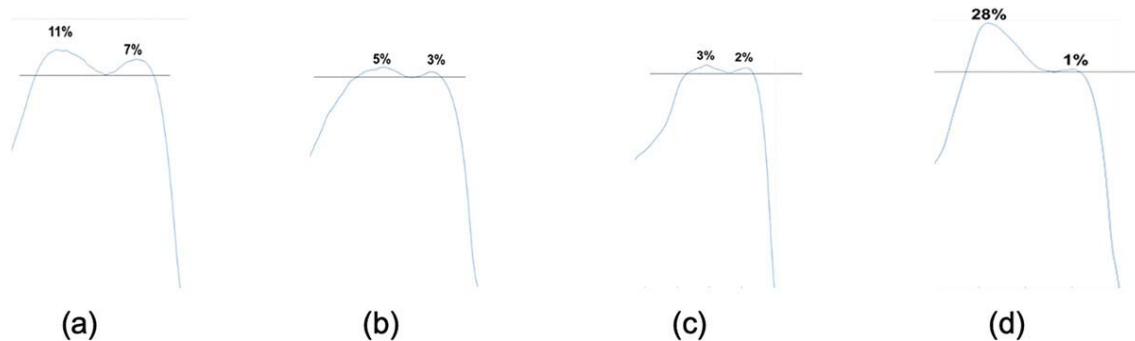


Figure 2. Examples from the dataset of the various prominence values for (partial) force-time curves with two visible peaks. Two larger prominences (a) are more distinct and likely to be visually categorised as bimodal, whereas the smaller prominences (b and c) are increasingly less likely to be categorised as bimodal. In some cases, one prominence is much larger than the other (d).

To address the third aim of the study, a minimum prominence threshold of 2% was applied, and the best jump performed by each participant (based on jump height) was included in the analysis. The outcome variables of jump height, RSImod and take-off momentum were compared between unimodal and bimodal groups using an independent samples t-test. A one-way ANOVA was applied to assess differences in jump outcome variables between the five subcategories, with Tukey post-hoc tests to identify where significant differences occurred if a significant group effect was found. Normality of distribution and equality of variance was confirmed before using parametric tests. Statistical significance was accepted at $p < 0.05$. A Cohen's d effect size, with 95% confidence intervals, was also calculated for all between-group comparisons (unimodal vs bimodal, and pairwise comparisons of the subcategories) to enable interpretation of the magnitude of the differences, using the following thresholds: trivial < 0.2 , small 0.2–0.6, moderate 0.6–1.2, large, 1.2–2.0 and very large > 2.0 (Hopkins, 2002).

Results

Six jump trials from 214 participants (mass: 97.5 ± 15.7 [58.1–128.4] kg, height: 181.0 ± 7.9 [163–216] cm) were included in the analysis. The participants' highest level of rugby representation was junior provincial (age 18–20 years, $n = 107$), senior provincial ($n = 58$, Super Rugby ($n = 41$) and international ($n = 8$). The mean jump height, based on each participant's best trial, was 38.7 ± 6.8 [22.7–60.4] cm. The mean maximum force was 2334.1 ± 413.6 [1347.8–3639.2] N (absolute) and 24.7 ± 2.7 [16.6–33.4] N/kg (relative).

Proportion of jumps in each category

The results of the sensitivity analysis are displayed in Figure 3. At a minimum prominence threshold of 0% (MPT₀), 54% of jumps were classified as bimodal. This decreased with each incremental adjustment; 43% at MPT₁, 34% at MPT₂, 28% at MPT₃, 22% at MPT₄ and 18% at MPT₅. For prominence thresholds greater than 20%, all jumps were classified as unimodal. For

jumps where F_{z2} values were detected for the given MPT value, both the average absolute threshold values in Newtons and the between-subject variance generally increased linearly with the MPT. From MPT_2 onwards, the mean thresholds were greater than the onset and offset detection threshold of 20 N used to detect the take-off and landing events.

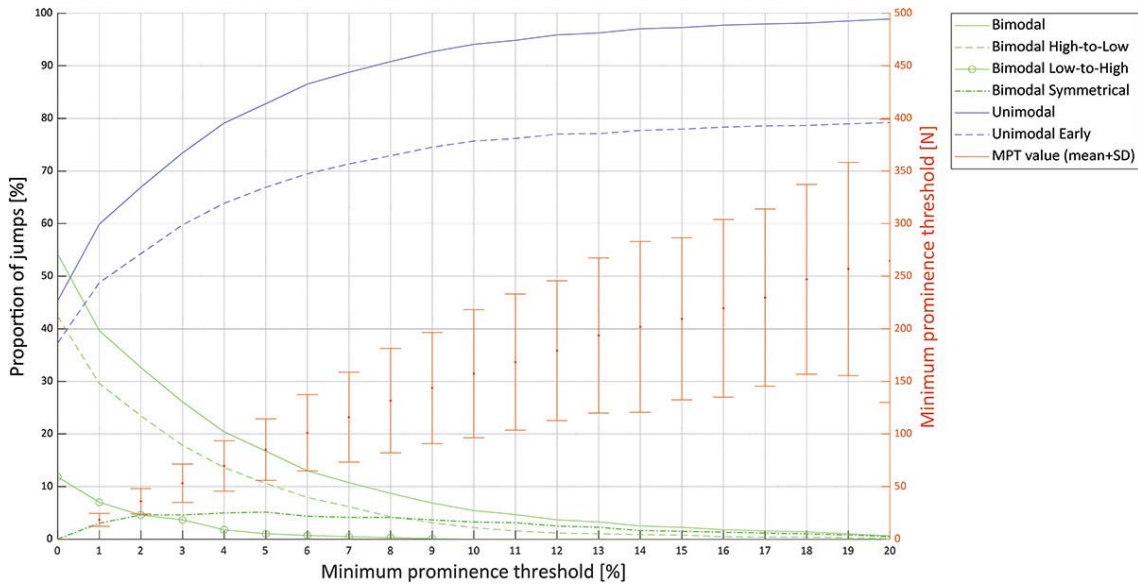


Figure 3. The effect of the minimum prominence threshold (MPT) on categorisation of force-time curve modality and the absolute Newton value of the threshold.

The proportion of jumps in each subcategory was also affected by the MPT, particularly in the bimodal category where the breakdown of High-to-Low, Low-to-High and Symmetrical in these subcategories was 76%, 24% and 0% at MPT_0 and 66%, 10% and 24% at MPT_5 . In the unimodal category, the proportional breakdown was more consistent: 85% were classified as Early at MPT_0 , and 81% were classified as Early at MPT_2 to MPT_5 .

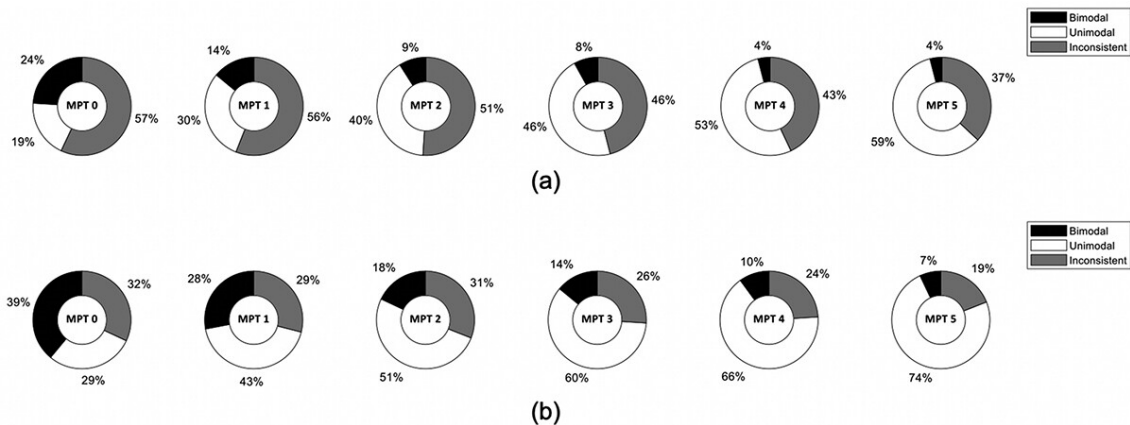


Figure 4. The effect of the MPT on the proportion of athletes ($n = 214$) that demonstrated consistent or inconsistent modality for (a) all 6 of their jumps and (b) at least 5 of their 6 jumps.

Within-athlete consistency

The results for within-athlete consistency (across six CMJ trials) were also affected by the MPT. Figure 4 illustrates that, across MPTs, 43% to 63% of athletes were consistent in their categorisation of all six jumps at the level of bimodal/unimodal classification. The proportion of athletes that were classified as either unimodal or bimodal in at least five out of six trials ranged from 68% (MPT₀) to 81% (MPT₅).

When considering within-athlete consistency at the level of subcategory, the proportion of athletes that were consistent across all six jumps was 33%, 35%, 39%, 40%, 45% and 47% (MPT₀ to MPT₅). Athletes that were consistent in at least five out of six trials ranged from 57% (MPT₀) to 67% (MPT₅). Subcategory consistency across six trials was higher for Early (26%, 33%, 36%, 40% and 42% at MPT₁₋₅) than High-to-Low (7%, 4%, 2%, 1% and 1%), Late (2%, 3%, 3%, 4% and 4%) and Low-to-High and Symmetrical (0% for MPT₁ and above).

Effect of force-time curve modality on jump performance

Performance variable comparisons between main and subcategories are shown in Figure 5. There was no effect of main category on jump height (unimodal: 37.8 ± 6.4 cm, bimodal: 38.6 ± 7.0 cm, $t = 0.795$, $p = 0.428$, $ES = 0.10$ (95% CI: $-0.17, 0.40$)) or take-off momentum (unimodal: 258.4 ± 34.5 kg.m.s⁻¹, bimodal: 256.2 ± 34.3 kg.m.s⁻¹, $t = 0.448$, $p = 0.655$, $ES = 0.06$ (95% CI: $-0.23, 0.35$)). RSI_{mod} was greater in the unimodal group (48.8 ± 11.3) than the bimodal group (44.9 ± 10.1 , $t = 2.544$, $p = 0.012$, $ES = 0.36$ (95% CI: $0.10, 0.65$)).

There was a significant effect of subcategory on RSI_{mod} ($F = 5.698$, $p < 0.001$) and take-off momentum ($F = 4.664$, $p = 0.001$), but not on jump height ($F = 0.210$, $p = 0.932$). Post hoc tests revealed that RSI_{mod} was significantly greater in the Early group than the Late ($p = 0.008$, $ES = 0.81$ (95% CI: $0.37, 1.25$)) and Low-to-High groups ($p = 0.011$, $ES = 0.88$ (95% CI: $0.38, 1.44$)). Take-off momentum was greater in the High-to-Low group compared to the Low-to-High ($p = 0.013$, $ES = 1.04$ (95% CI: $0.42, 1.73$)) and Symmetrical groups ($p = 0.047$, $ES = 1.01$ (95% CI: $0.16, 1.89$)), and in the Early group compared to the Low-to-High group ($p = 0.042$, $ES = 0.80$ (95% CI: $0.26, 1.40$)).

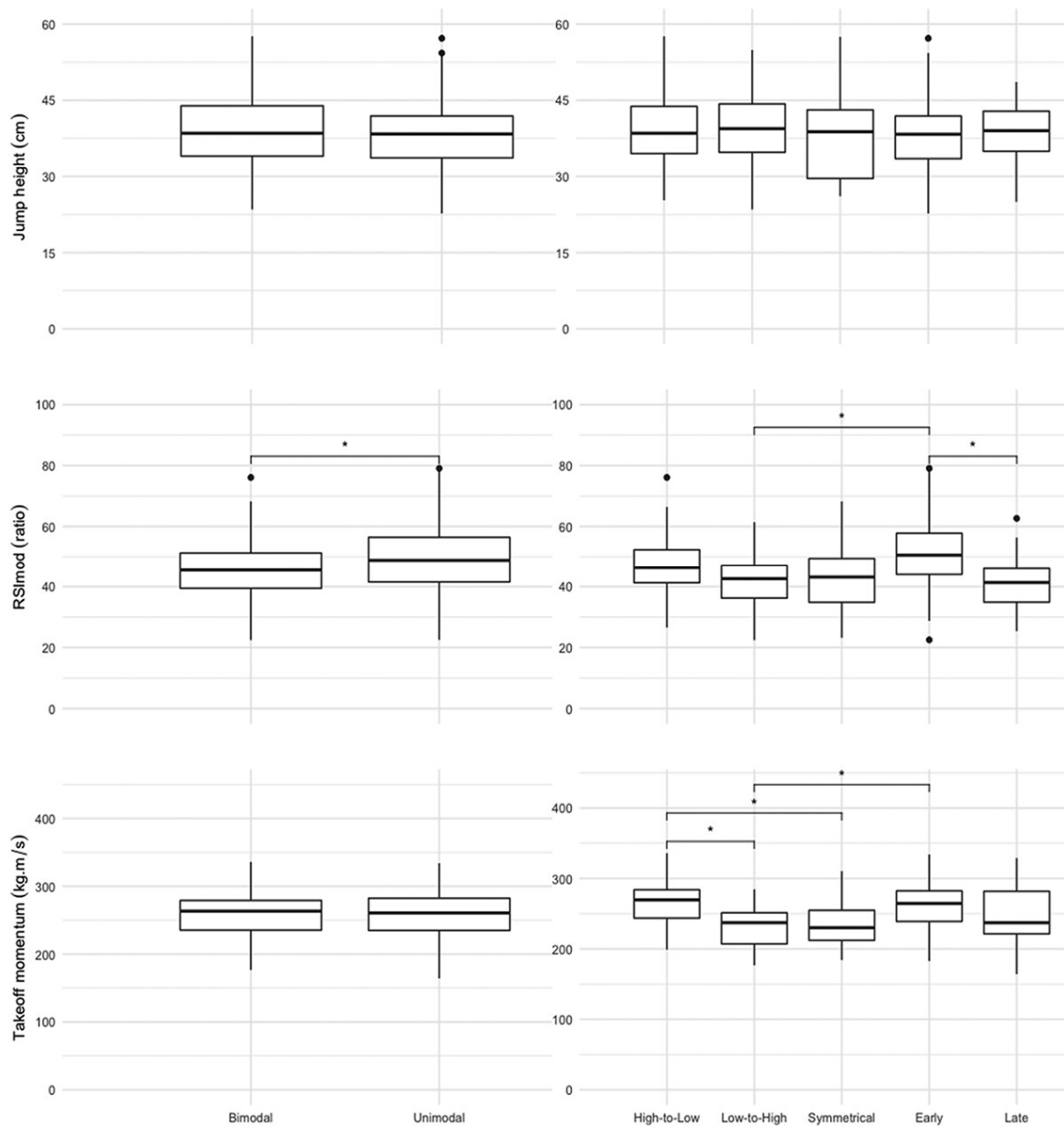


Figure 5. Countermovement jump performance in unimodal and bimodal jumps and subcategories. * Statistically significant between-group differences ($p < 0.05$).

Discussion and implications

The first two aims of the study were to assess the effect of varying objective thresholds for the categorisation of CMJ force-time curve shapes on the prevalence of different curve shapes and within-athlete consistency. More than half of the jumps were categorised as bimodal at MPT_0 but this proportion decreased substantially with each increase in the minimum prominence threshold to only 18% (one-third of the proportion found at MPT_0) at MPT_5 . This finding supports our first hypothesis and indicates that bimodality classification is highly sensitive to small changes in the CMJ force-time curve pattern and thus likely to be inconsistent on visual inspection by human raters. Second, within-athlete consistency in classification varied moderately with small changes in the MPT, where between 43% (MPT_0) and 63% (MPT_5) of participants were categorised consistently as either bimodal or unimodal across all six jumps.

This finding supports our second hypothesis that consistency would increase with an increase in MPT. The third aim was to assess differences in CMJ performance measures between unimodal and bimodal jumpers as well as between the five subcategories. Our third hypothesis was partially supported, as there was no effect of force-time curve shape category on jump height or take-off momentum, but RSImod was greater in the unimodal jumps. Analysis of the subcategories revealed that the unimodal Early and bimodal High-to-Low outperformed the other subcategories in both RSImod and take-off momentum. This highlights the need to consider force-time curve shape variations within bimodal and unimodal categories and suggests that the timing of peak vertical force may be more relevant to jump performance than the force-time curve modality.

An objective approach is preferred over subjective visual inspection to enhance the repeatability of force-time curve categorisation and enable comparison between studies. In the current study, we have presented an objective method based on the selection of a threshold of percentage change in bimodal peaks during the concentric phase of the CMJ. As a frame of reference, the GRF magnitude of the 1%, 2% and 3% MPT was 18 ± 3 N, 37 ± 6 N and 54 ± 9 N, respectively, in this cohort and the categorisation of jumps was shown to be sensitive to these different thresholds. We propose that a minimum prominence threshold of 2% be used to categorise jumps—this is likely to be a smaller absolute N value in many other cohorts, as the mass (mean: 97.5 kg) and maximum force (mean: 2334 N) of the participants in the current study was high. Regardless of the methods used, the authors should clearly describe the objective classification criteria in future studies. It should also be noted that an automated objective method does not negate the need for careful assessment of data quality, where visual inspection may be one component of identifying errors or outliers in the dataset.

The proportion of bimodal jumps in the current study was 54% at MPT₀ (the threshold most sensitive to bimodality), which is similar to a comparable population of 33 academy rugby players (52%) (Kennedy & Drake, 2018). This might imply that the researchers employed a similarly sensitive visual inspection approach. However, bimodality prevalence much higher than the MPT₀ ceiling for our algorithm in this study has been reported in college athletes in multiple sports codes (78%–87%) (Lake & McMahon, 2018; McHugh et al., 2021) which seems to suggest that the differences are not caused by classification methods alone. The physical profile of athletes and the training demands within specific sports may be related to force production strategies or capabilities, and further research is warranted to understand the prevalence of different force-time curve shapes in different sporting codes.

Consistency of unimodal/bimodal categorisation across all six jumps was lower in the current cohort (49% at MPT₀ and MPT₂) than across five (67%) or ten trials (60%) in a study involving 15 university-level athletes (Lake & McMahon, 2018). Allowing for some expected variation in human performance, still only ~70% of athletes was consistently bimodal or unimodal across five out of the six jumps. When taking subcategories into account, only 33%–47% of athletes were consistent across all six trials and 57%–67% in at least five out of six trials. Therefore, classifying an athlete as a ‘unimodal jumper’ or ‘bimodal jumper’ or any of the subcategories defined in this study should be done with caution and individual variability must be considered. Consistency was much higher for the Early subcategory than any of the other, with 26% of participants being consistent across six jumps when using the MPT₁ (33% at MPT₂). This could indicate that a single peak early in the concentric phase may be a more biomechanically efficient force profile than the other variations observed.

Previous research has been inconclusive as to whether a unimodal or bimodal force-time curve represents a better CMJ performance strategy (Cormie et al., 2009; Kennedy & Drake, 2018; Peng et al., 2019). A training intervention study that led to CMJ improvements in power, rate of force development and jump height was associated with a shift to a bimodal force-time curve, which the authors attributed to improved stretch shortening cycle utilisation (Cormie et al., 2009). Peng and colleagues reported greater jump height and RSImod in physical education students that were classified as bimodal jumpers compared to unimodal jumpers (Peng et al., 2019). In contrast, Kennedy and Drake found unclear differences in these parameters between unimodal and bimodal groups but concluded that the bimodal strategy was an inefficient use of the stretch shortening cycle based on the ratio of negative impulse to positive impulse (Kennedy & Drake, 2018). At the level of bimodal versus unimodal comparison, the current study does not add further clarity to this debate, as jump height and take-off momentum were similar between groups although RSImod was greater in the unimodal jumps. However, on analysis of the subcategories, it was found that a unimodal curve where the peak occurs in the first half of the concentric phase and a bimodal curve where the first peak is higher than the second were associated with greater RSImod and take-off momentum. The inconsistency in the evidence for a relationship between modality and jump performance to date may be due to previous studies not having accounted for variations within the main categories. For example, in the intervention study by Cormie and colleagues (Cormie et al., 2009), the group mean data displayed a ‘unimodal late’ profile at baseline and a bimodal curve post-training. The performance improvement could be attributed to a shift in the timing of maximum force, occurring earlier in the concentric phase, rather than a change from unimodal to bimodal. Collectively, these results suggest that the timing of maximum force may be more important than the modality of the curve for jump performance. An analysis of the jumps of 100 collegiate athletes concluded that the optimal CMJ force-time profile is one in which peak force occurs at the transition point between the eccentric and concentric phase regardless of its modality (McHugh et al., 2021). Although we did not analyse the precise timing of the force peak relative to the start of the concentric phase, our findings provide a similar observation that maximum force occurring early in the concentric phase (at or near the lowest position of the countermovement) is beneficial for performance. In the present cohort, most jumps were either High-to-Low (25%) or Early (53%) at MPT₂. Peak force in the first portion of the concentric phase therefore appears to be the preferred strategy in this population, regardless of whether there is a second smaller peak.

Conclusion

This study has demonstrated that the categorisation of CMJ force-time curve shapes is sensitive to different thresholds. We therefore recommend the use of objective criteria in future studies to enhance transparency and comparability. We propose a minimum prominence threshold of 2% using the methods described in this study. Furthermore, the categorisation of jumps as unimodal or bimodal without considering the timing or relative magnitude of the force peaks may mask important implications for jump performance. Subcategories defined in this study should therefore be considered when investigating differences in CMJ strategies.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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