A LARGE-SCALE NUMERICAL ANALYSIS OF UNIMODAL AND BIMODAL FEATURES IN FORCE PLATE DATA MEASURED DURING VERTICAL COUNTERMOVEMENT JUMPING

John Cockcroft[1], Aneurin Robyn[2], Quinette Louw[2] and Helen Bayne[3]

Neuromechanics Unit, Stellenbosch University, South Africa[1]
Division of Physiotherapy, Stellenbosch University, South Africa[2]
Division of Biokinetics and Sport Science, University of Pretoria, South Africa[3]

This study presents a novel algorithm for automatically analyzing modality patterns in countermovement jump (CMJ) force-time curves. Bimodal peaks (F_{z1}, F_{z3}) are identified using a minimum threshold (T_{trough_drop}) for their relative drop to the intermediate trough value (F_{z2}). In a large sample of athletes (n = 214), 75% of jumps were technically bimodal (T_{trough_drop} > 0%) but this decreased to 17% (T_{trough_drop} > 5%) and 0% (T_{trough_drop} > 20%) using alternative definitions. This suggests that conflicting findings in other studies may be explained by a lack of standardized criteria for classifying modality. The drop from F_{z1} to F_{z2} in bimodal jumps was also largely correlated (r = 0.75) to the force at zero velocity and braking acceleration (r = 0.63). These findings highlight the potential value of extracting new quantitative features related to curve modality for CMJ research and interpretation.

KEYWORDS: countermovement jumping, force, bimodal.

INTRODUCTION: Vertical countermovement jumps (CMJs) are widely used to assess neuromuscular function in athletes. In high performance settings, force plate analysis has proliferated recently because it is thought to provide additional insight into the factors influencing CMJ performance. However, despite the established usefulness of discrete force-time variables for practitioners monitoring athlete conditioning or rehabilitation, features describing the shape characteristics of CMJ waveforms remain under-utilized and poorly understood (Lake & McMahon, 2018). Therefore, analyses of the entire CMJ force-time curve have gained popularity as researchers seek to more effectively interpret force plate data.
Studies of CMJ force-time patterns have typically reported either a unimodal or bimodal shape during the propulsion phase (Cormie, McBride, & McCauley, 2009). However, studies have reported very different prevalence rates of bimodality for groups as well as individuals, and its relationship to jump performance is debated (Kennedy & Drake, 2018). One possible explanation for this lack of clarity is that many studies categorize modality by visual inspection in a small sample of jumpers (n < 50), and do not quantify features directly related to modality. Furthermore, no studies have attempted to investigate the relationship between variables describing the braking phase of a CMJ, and the subsequent drop in force between bimodal peaks. This is an important consideration, since the eccentric phase of the CMJ creates the initial conditions for propulsion and thus influences the utilization of the stretch-shorting cycle. Therefore, this study aimed to describe CMJ modality in a large cohort of athletes using standardized criteria and to answer the following research questions:

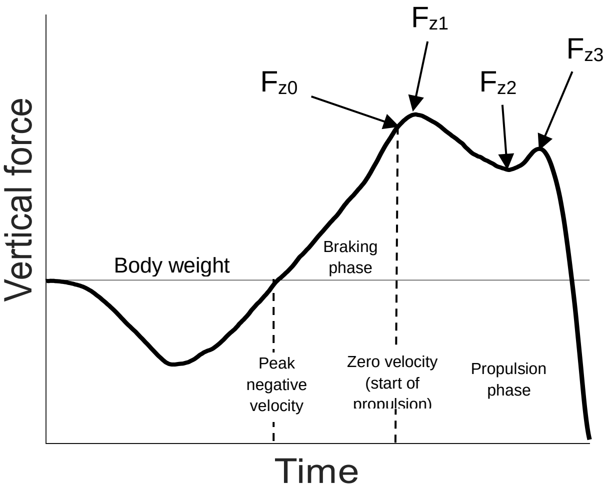
1. Is the prevalence of uni- and bimodal curves highly sensitive to classification criteria?

2. Does the force drop between bimodal peaks correlate strongly with any particular braking phase outcomes?

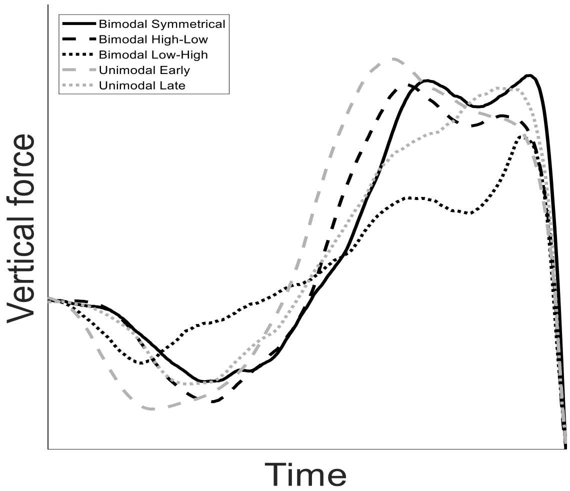
METHODS:

A descriptive study was performed on a large convenience sample (*n*: 214, mass: 97.5 ± 15.7 [58.1 – 128.4] kg) of provincial level rugby union players in South Africa. Only male rugby players available for competition were included, and participants were excluded if they had incurred lower limb injuries less than six months before the study. The study was approved by the Stellenbosch University Ethics Committee and participants gave informed consent before testing. The protocol included a standardized ten minute warm-up procedure involving stretching and running drills and then a test battery of six vertical, unloaded CMJs with hands on hips and no arm swing. The CMJs were executed in three sets of two, with the two jumps in a set separated by 20 seconds and each set separated by two minutes of rest. Participants were cued to “jump as high as possible”. Testing was conducted in an indoor laboratory on a floor-level, force-instrumented treadmill (Bertec Corporation, USA) bolted to the floor. Force offsets were digitally zeroed out after each set of two jumps to minimize drift errors.

Data processing to detect body weight and CMJ temporal phases was performed in a custom Matlab script (v2017a, Mathworks Inc, USA) utilizing standard thresholds and impulse-momentum calculations. The script also performed the modality analysis, which searched forwards in time for the start of propulsion for the first two force peaks (F_{z1} and F_{z3}) using turning points in the force-time series (Figure 1a). Unimodal curves were defined as having no identifiable F_{z3}. To avoid peak detection for minor ripples in the force, F_{z1} and F_{z3} were only taken as valid if they both exceeded the minimum force between them (F_{z2}) by a certain percentage (T_{trough_drop}). Bimodal curves were also sub-grouped as either High-to-Low ((F_{z1} - F_{z3}) / F_{z1} > T_{trough_drop}), Low-to-High ((F_{z3} - F_{z1}) / F_{z3} > T_{trough_drop}) or Symmetrical (Figure 1b). Unimodal curves were sub-grouped into Early or Late categories based on whether F_{z1} occured in the first or second half of the propulsion phase. A sensitivity analysis was conducted on the effect of T_{trough_drop} values (0% through to 20%) on modality classification. For T_{trough_drop} > 5%, an analysis was performed on the bimodal jumps (using the Pearson’s correlation coefficient) to assess the association between drop in force after F_{z1} (dF_{z1-2}) and braking phase variables: peak braking velocity V_b, braking phase time T_b, peak braking displacement D_b and average braking acceleration A_b. A_b was calculated as V_b / T_b. The correlation between F_{z0} and braking acceleration was also performed on the unimodal group.



(a) Modality features extracted from curve



(b) Subgrouping using modality features

Figure 1: Illustration of the CMJ modality features and examples of different classifications

RESULTS: The value of the threshold criteria (T_{trough_drop}) had a major effect on modality classification (Figure 2). Using a technical definition of bimodality (T_{trough_drop} > 0%), over 70% of CMJs was categorized as bimodal. However, bimodal prevalence dropped under 10% after T_{trough_drop} > 8%, and almost all jumps were classified as unimodal from T_{trough_drop} > 20%. Peak forces in the first half of the propulsion phase (Bimodal High-Low and Unimodal Early) were much more prevalent than in the second half. The relative proportions of the modality subgroups (e.g. percentage of Unimodal Early) were largely insensitive to the threshold value.

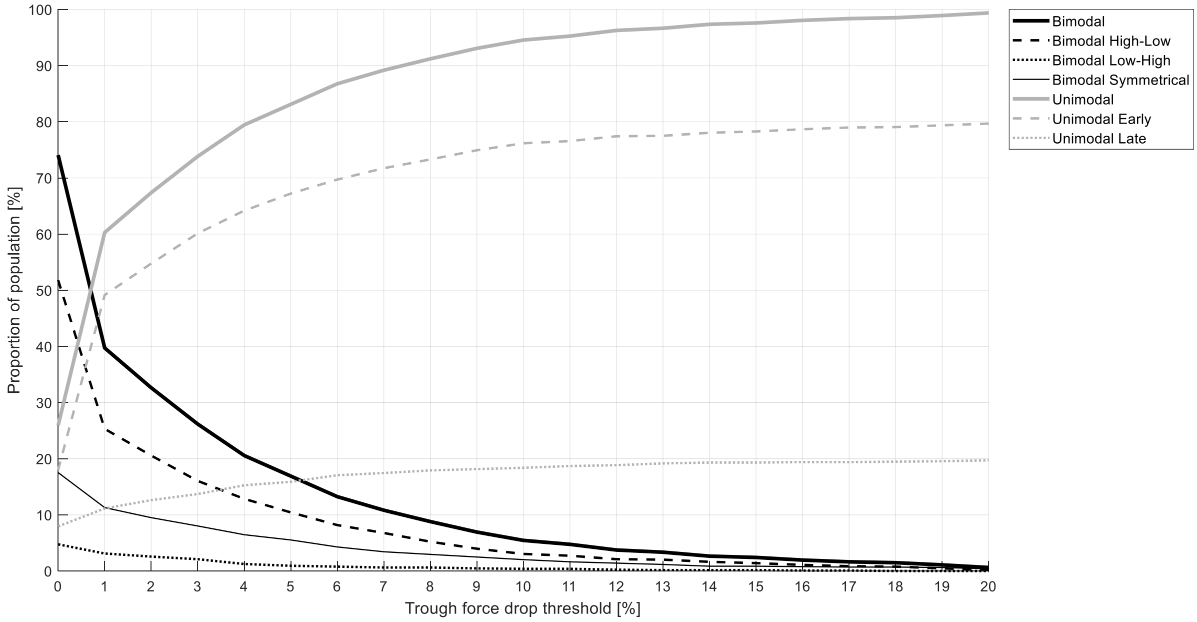


Figure 2: Influence of the minimum bimodal trough force drop threshold on modality classification

In the correlation analysis data set (T_{trough_drop} > 5%), 217 (16.9%) of the 1284 analyzed CMJs we classified as bimodal and only 8 (3.7%) of the participants performed bimodal jumps for every CMJ. This intra-subject variability was also reflected in a higher proportion of participants demonstrating bimodality in at least one (39.3%) and more than half (11.2%) of their six CMJs. dF_{2-1} showed a very large association with F_{z0} and a large association with A_b (Table 1). It also showed a large correlation with V_b, but only a moderate correlation with D_b and T_b. It was also observed that F_{z0} had a very large correlation with A_b in both the bimodal (r = 0.86) and unimodal (r = 0.88) subgroups.

Table 1: Braking phase variables and their correlation to magnitude of the trough drop value dF_{2-1} within the bimodal subgroup classified using threshold T_{trough_drop} > 5%

Description	Abbreviation	Units	Value (Mean ± SD [min – max])	Correlation with dF_{2-1} (r)
Drop from F_{z1} to F_{z2}	dF_{2-1}	%	17.9 ± 9.2 [5.1 – 44.7]	-
Braking phase time	T_b	ms	180 ± 58 [57 – 694]	-0.37
Peak COM braking displacement	D_b	cm	33.8 ± 6.3 [2 – 55]	0.32
Peak COM braking velocity	V_b	$m.s^{-1}$	1.15 ± 0.25 [0.11 – 1.82]	0.55
Average COM braking deceleration	A_b	$m.s^{-2}$	7.5 ± 2.7 [0.5 – 16.9]	0.63
Normalized force at zero velocity	F_{z0}	N/kg	23.7 ± 3.25 [10.9 – 35.8]	0.75

DISCUSSION: This study found that the reported prevalence of CMJ bimodality in a large population was highly sensitive to the definition of bimodality applied. In particular, the threshold applied to the relative amplitudes of force turning points affected the identification of bimodal peaks, such that a threshold value of 1% classified twice as many bimodal jumps as a 4% threshold (Figure 2). This suggests that there may be a high risk of subjectivity in classifications performed by visual inspection in the literature, potentially leading to non-standardized subgroupings and pooling of data that are poorly-matched to other studies. The risk that this poses to null-hypothesis testing has been highlighted by other researchers (Kennedy & Drake, 2018) and highlights the need for standardization in the research community. Similarly, the variability in CMJ modality observed for individual participants also suggests that care should be taken when averaging force-time curves or selecting representative participant variables to perform inferential statistics.

The decrease in force after the initial peak in the bimodal group was associated with a higher peak velocity at the start of the braking phase, greater average braking acceleration, higher force at zero velocity and (to a lesser extent) greater braking displacement and a shorter braking phase. Interestingly, similar correlations were observed for A_b and F_{z0} in the bimodal and unimodal jumps. This suggests that differences exist between athletes in their ability to transition from braking to propulsion under high vertical force. A consistently large T_{trough_drop} may indicate under-utilization of the stretch shortening cycle or poor eccentric control simply due to excessive braking velocity. Future research should aim to elucidate this.

This study is limited by the use of linear correlations to analyse the association between individual outcomes and the drop from first bimodal force peak to the trough value. While the use of braking acceleration (a ratio of two traditional outcomes) did reveal a better association than the individual outcomes, more advanced regression analysis may provide more insight into the mechanisms underpinning bimodality. Secondly, although the sample was relatively large compared to other studies, variability in the jumping ability was relatively high due to the heterogeneity of the group, which included athletes from a range of different playing positions in their rugby union teams. Nevertheless, this study remains relevant to researchers and practitioners seeking reliable and efficient computational tools to analyse CMJs.

CONCLUSION: This study contributes towards the standardization of CMJ analysis. It presents the first description of CMJ bimodality in a large cohort using a novel quantitative approach. Strong correlations between modality features and traditional braking phase variables were reported. This method offers advantages over current best practise of visual observation because it is objective and automatic while remaining simple and intuitive.

REFERENCES:

Cormie, P., McBride, J., & McCauley, G. (2009). Power-time, force-time, and velocity-time curve analysis of. *J. Strength Cond. Res.*, 177–186.

Kennedy, R. A., & Drake, D. (2018). Is a Bimodal Force-Time Curve Related to Countermovement Jump Performance? *Sports*, 36-49.

Lake, J., & McMahon, J. (2018). Within-Subject Consistency of Unimodal and Bimodal Force Application during the Countermovement Jump. *Sports* , 143-151.

McMaster, D. (2016). A comparison of unimodal and bimodal countermovement jump force-time curves. *Proceedings of the Sport and Exercise Science New Zealand Conference.* Cambridge.