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Is there a biomechanically efficient vertical ground reaction force profile for countermovement jumps?

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Abstract

The purpose of this study was to determine whether countermovement jump (CMJ) metrics differed based on whether or not peak vertical ground reaction force (GRF) occurred at the lowest point of the countermovement (low position). CMJs from 100 athletes were categorized based on whether or not the peak force occurred at low position and whether they had unimodal or bimodal GRF profiles. CMJ metrics were compared between jump categories and between athletes with above average, average, and below average jump heights. Peak force occurred at low position in 52% of jumps. The majority of jumps were bimodal (78%) and in 73% of bimodal jumps the first peak was higher than the second peak. Both performance metrics (5% higher jump, 25% greater reactive strength index) and most braking phase metrics were superior for jumps in which peak force coincided with low position ($P < .01$). Peak force occurred at low position in 76% of above average jumps, 50% of average jumps, and 37% of below average jumps ($P = .019$). The optimal profile for CMJ performance is one in which peak force occurs at low position, regardless of whether it is unimodal or bimodal. This provides a qualitative means of identifying biomechanically efficient jumps.

KEYWORDS

bimodal, biomechanics, eccentric, elastic energy, force plate, unimodal

1 | INTRODUCTION

Measurement of vertical ground reaction force (GRF) during countermovement jumps (CMJ) has become a common method of assessing lower extremity power in athletes across a range of sports.[1-3] These tests are typically performed with the hands on the hips (often referred to as akimbo) to eliminate the added momentum generated from arm swing.[4-7] Studies examining the biomechanics of akimbo CMJs often report peak braking (eccentric) and propulsive (concentric) forces among a list of metrics from the different phases of a CMJ.[8-11] In such studies the low position of center of mass (COM) during the countermovement represents the end of the braking phase and the start of the propulsive phase. One problem with reporting a distinct peak braking force and a distinct peak propulsive force is that peak vertical GRF may occur at the low point of the countermovement, and thus, peak braking and peak propulsive forces would be the same point.

There is much disparity in the literature on the occurrence of peak GRF relative to low position in CMJs with arms akimbo. Several studies have reported values for force at low position (zero velocity) and peak concentric (propulsive) force.[3,8,9,12] In these studies force at low position as a percentage of peak concentric force was 65%,[3] 89%,[8] 90%,[9] and 110%.[12] Other studies have graphically displayed the

GRF profile with indication of COM low position.[4,10,12-22] In one study the GRF ensemble average showed peak force occurring at low position.[4] Studies showing GRF graphs of selected subjects have shown different profiles, with peak force occurring at low position,[12,13,16,18-20] after low position,[14,15,21,22] or even before low position.[10] Two studies reported three different values for peak eccentric force, force at low position, and peak concentric force.[3,9] In both studies peak concentric force was highest, but confusingly peak eccentric force was higher than force at low position. Similarly, Aboodarba et al[8] reported peak concentric force to be higher than peak eccentric force but also reported force at the end of the eccentric phase to be lower than peak eccentric force. Biomechanically this does not make sense. The purpose of the eccentric phase of a jump is to store elastic energy in the muscle tendon units of the prime movers to augment COM propulsion.[23-26] Elastic energy is best utilized by a rapid transition from the eccentric countermovement to the concentric propulsion.[12] A rapid transition from countermovement to propulsion would equate to maximal acceleration occurring during this phase and would be evident in peak force occurring at low position. Having a higher force prior to low position and a higher force after low positions would be biomechanically inefficient. However, the relationship between peak force and low position has not been investigated with respect to other biomechanical jump metrics or jump performance. Therefore, the primary purpose of this study was to differentiate jump metrics between jumps in which peak force occurred at low position vs those jumps in which peak force did not occur at low position. It was hypothesized that CMJ metrics would be superior for jumps in which peak force occurred at low position.

Part of the confusion in the literature with regard to interpreting conflicting CMJ metrics is that jumpers display a variety of GRF profiles, including jumps with single peaks (unimodal) or double peaks (bimodal). A secondary purpose of this study was to examine the extent to which CMJ metrics differed between unimodal and bimodal jumps. It was hypothesized that CMJ metrics would be inferior for bimodal jumps in which the second peak was higher than the first peak because the second peak would be occurring during the propulsive phase (after low position). Thus, this study aimed to test the hypothesis that CMJs in which peak force occurs at low position are biomechanically efficient jumps.

2 | MATERIALS AND METHODS

2.1 | Participants

The GRF profiles of CMJs from NCAA Division I athletes from a single institution were examined. The jumps were part of routine monitoring of the athletes and were performed by the strength and conditioning staff following a standardized protocol. Only jumps with arms akimbo were examined. To ensure that the jumps were maximal efforts, unencumbered by fatigue or other confounding factors, the top 100 jumps were selected from the database with only one jump per athlete included in the analyses. The final sample comprised 100 male athletes (age 21 ± 3 years, height 1.85 ± 0.89 m, body mass 83.4 ± 10.2 kg) of which 33 played hockey, 25 lacrosse, 14 soccer, 14 basketball, and 14 from other sports (track, field hockey, football, rugby, skiing). All jumps were performed as part of the athlete's performance monitoring by the strength and conditioning staff. Institutional review board approval was granted, in the spirit of the Helsinki Declaration.

2.2 | Procedures

The jump protocol was standardized across all athletes and all teams for all test sessions. Following a standardized 5 minutes warm-up, athletes performed three maximum CMJs with arms akimbo. The warm-up consisted of 10 bodyweight squats, five drop squats, 10 reverse lunges with overhead reach, five practice jumps with arms akimbo and with increasing intensity with each jump. All jumps were performed before the athletes participated in any physical activity on a given day. The only instruction was to jump as high as possible. Jumps were performed on dual force plates (acquisition 1 kHz, resolution 0.25 N, range of 0-14 kN) (Hawkin Dynamics) and processed using custom software (Hawkin Cloud). The summated data from both plates was analyzed.

2.2.1 | CMJ profiles and jump metrics

Jumps were categorized based on whether or not peak force occurred at low position. If force at low position was within 1% of peak force it was categorized as occurring at low position. Jumps were categorized as unimodal if force declined continuously after the initial peak or if force declined and then plateaued before declining to zero. Jumps that showed an initial peak followed by a decline and then second peak were categorized as bimodal. Bimodal jumps were further categorized based on whether the first or second peak was higher. If peaks were within 1% of each other they were categorized as equal.

The GRF profiles were separated into three phases (Figure 1): (a) the unweighting phase (from initiation of countermovement to nadir in negative velocity, at which point acceleration is zero and GRF is equal to baseline force due to body weight); (b) the braking phase (from nadir in negative velocity to the low position of the countermovement); (c) the propulsive phase (from low position to take-off). There were two unweighting phase metrics, seven braking phase metrics,

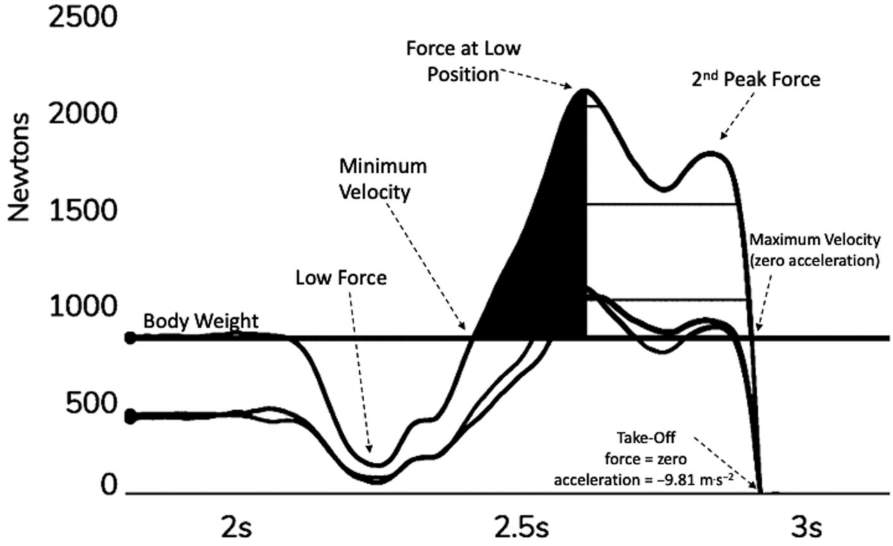

FIGURE 1 A sample graph of a bimodal CMJ with peak force occurring at low position. The single solid black line that begins at approximately 800 N (body weight) is the summation of the forces from both force plates (the force from each force plate is shown below the summated line). The unshaded area where force is below body weight (nadir at low force) indicates the unweighting phase ending at the nadir for negative velocity (zero acceleration/return to baseline force due to body weight). The black shaded area indicates the braking (eccentric) phase ending at the low point of the countermovement (zero velocity). The area with horizontal black lines indicates the propulsive (concentric) phase ending at take-off (force = zero, acceleration = −9.81 m/s)

three propulsive phase metrics and two performance metrics (Table 1).

2.3 | Statistical analyses

Normality of distribution was confirmed for all metrics using the Shapiro-Wilk tests. Independent samples *t* tests were used to compare metrics between jumps in which peak force did, or did not, occur at low position and between unimodal and bimodal jumps. For bimodal jumps independent sample *t* tests were used to compare jumps between those in which the first peak was higher vs those in which the second peak was higher (since there were only five jumps in which the two peaks were equal these jumps were left out of the analyses).

Jump heights were categorized as above average (>1 SD above mean), average (within 1 SD of mean), or below average (>1 SD below mean) with proportions compared between jumps in which peak force did or did not occur at low position and between unimodal and bimodal jumps. using chi-square linear effect analysis. One-way ANOVA was used to compare jump metrics between above average, average, and below average jumps with Bonferroni corrections for pairwise comparisons. Mean ± SD is reported in text and tables.

Jump metrics were not compared between athletes from different sports since the sample consisted of the athletes with highest jump heights across all athletes tested and, therefore, the players were not representative of the players from each sport. Similarly, reproducibility of jump metrics was not assessed in these athletes since the index jumps were selected based on superior performance and jumps on other occasions would by definition be inferior. The reproducibility of most metrics has been reported previously.[3]

3 | RESULTS

3.1 | CMJ GRF profiles

Peak force occurred at low position in 52 of the 100 jumps, 22 of 100 were unimodal (14 with peak force at low position, eight after low position). Of the 78 bimodal CMJs, the first peak was higher in 57 (34 at low position, 19 after low position, four before low position), the peaks were equal in five (four at low position, one after low position), and the second peak was higher in 16 (peak force after low position for all). Thus, there were eight distinct jump profiles based on whether or not peak force occurred at low position, whether the jumps were unimodal or bimodal, and whether bimodal jumps were first peak dominant or second peak dominant (Figure 2).

3.2 | Force at low position relative to peak force

Nine of 14 jump metrics differed between the 52 jumps in which peak force occurred at low position vs the other 48 jumps (Table 2): 41% lower low force (*P* = .001), 19% shorter braking duration (*P* = .001), 46% greater braking RFD (*P* = .001), 38% greater braking power (*P* = .001), 25%

TABLE 1 CMJ metrics

CMJ metric	Operational definition
Unweighting phase metrics	
Low force (% BW)	Force nadir during unweighting
Unweighting duration (s)	Time from initiation of unweighting to low force
Braking phase metrics	
Countermovement depth (m)	Duration of lowering of center of mass from standing position to low position calculated from double integration of acceleration
Peak braking power (W/kg)	Peak value of the product of force and velocity between the nadir in negative velocity and low position
Force at low position (%BW)	Force at the low point of the countermovement
Braking RFD (% BW/s)	Increase in force from low velocity to low position divided by duration
Eccentric force (%BW)	Increase in force from low force to force at low position
Eccentric stiffness (N/m)	Eccentric force divided by countermovement depth
Braking duration (s)	Time from low force to low position
Propulsive phase metrics	
Peak propulsive power (W/kg)	Peak value of the product of force and velocity between low position and take-off
Mean propulsive force (%BW)	Average force from low position to take-off
Propulsive duration (s)	Time from low position to take-off
Performance metrics	
Jump height (m)	Calculated from take-off velocity where take-off velocity (m/s) equals net propulsive impulse (N/s) divided by body mass (kg)
RSI (ratio)	Flight time divided by time from initiation of unweighting to take-off

Abbreviations: BW, body weight (N); RFD, rate of force development; RSI, reactive strength index.

greater eccentric force ($P = .001$), 19% greater eccentric stiffness ($P = .002$), 17% higher force at low position ($P = .001$), 4% greater jump height ($P = .028$), and 11% higher RSI ($P = .003$). Unweighting duration, countermovement depth, peak propulsive power, mean propulsive force, and propulsive duration did not differ between jump types.

3.3 | Unimodal versus bimodal jumps

Neither unweighting phase metrics differed between unimodal (n = 22) and bimodal jumps (n = 78): duration of unweighting phase 0.382 ± 0.097 seconds vs 0.413 ± 0.181 seconds, $P = .436$; low force 22 ± 17%BW vs. 27 ± 17%BW, $P = .290$). All seven braking phase metrics differed between unimodal and bimodal jumps: unimodal jumps had a smaller countermovement (0.341 ± 0.052 m vs 0.383 ± 0.045 m, $P < .001$), a shorter braking phase duration (0.141 ± 0.022 seconds vs 0.185 ± 0.048 seconds, $P < .001$), greater eccentric stiffness (6.51 ± 1.37 kN/m vs 4.65 ± 1.18 kN/m $P < .001$), higher eccentric force (259 ± 43%BW vs 218 ± 43%BW, $P < .001$), greater braking power (23.9 ± 7.0 W/kg vs 20.1 ± 5.6 W/kg, $P = .011$), greater braking RFD (134 ± 35%BW/s vs 85 ± 29%BW/s, $P < .001$), and higher force at low position (281 ± 30%BW vs 244 ± 31%BW, $P < .001$). Two of the three propulsive phase metrics differed between unimodal and bimodal jumps: faster propulsive phase (0.239 ± 0.028 seconds vs 0.281 ± 0.030 seconds, $P < .001$), higher mean propulsive force (227 ± 17%BW vs 207 ± 13%BW, $P < .001$) but no difference in peak propulsive power (60.1 ± 6.3 W/kg vs 57.8 ± 4.9 W/kg, $P = .069$). Of the two performance metrics, RSI was higher for unimodal jumps (0.815 ± 0.110 vs 0.715 ± 0.129, $P = .001$) but jump height did not differ between jump types (0.440 ± 0.035 m vs 0.431 ± 0.041 m, $P = .315$).

3.4 | First peak dominant versus second peak dominant bimodal CMJs

Within the 78 bimodal jumps 7 of the 14 metrics differed between first peak dominant and second peak dominant jumps (Table 3). First peak dominant jumps had 35% lower low force, 40% greater peak braking power, 24% greater force at low position, 83% greater braking RFD, 38% greater eccentric force, 24% greater eccentric stiffness and a 28% shorter braking duration.

3.5 | Above average versus below average jumpers

Peak GRF occurred at low position for 76% of above average jumps (13 of 17) vs 50% of average jumps (32 of 64) and only 37% of below average jumps (7 of 19, linear effect $P = .019$). Thirteen of 52 (25%) jumps in which peak force occurred at low position were above average vs 4 of the 48 (8%) jumps in which peak force did not occur at low position ($P = .034$). The proportion of unimodal vs bimodal jumps did not differ between above average, average, and below average jumpers ($P = .564$). However, for the 78 bimodal jumps the first peak was greater than the second peak for 77% (10 of 13) of above average jumps, 61% (30 of 49) of average jumps and only 44% (7 of 16) of below average jumps (linear effect $P = .033$).

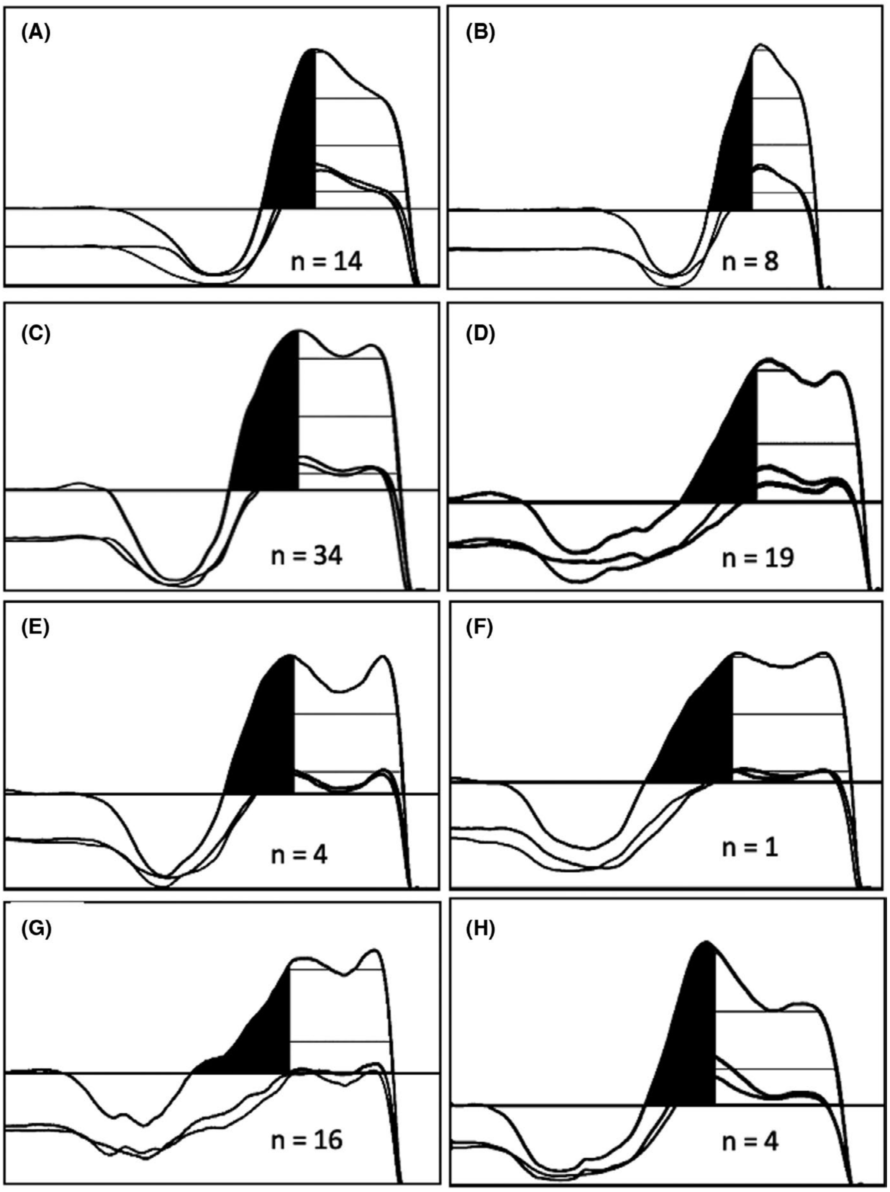

FIGURE 2 GRF jump profiles for different types of jumps observed. A, unimodal, peak force at low position (n = 14). B, unimodal, peak force after low position (n = 8). C, bimodal, first peak greater than second peak, peak force at low position (n = 34). D, bimodal, first peak greater than second peak, peak force after low position (n = 19). E, bimodal, first and second peak equal, first peak at low position (n = 4). F, bimodal, first and second peak equal, first peak after low position (n = 1). G, bimodal, second peak greater than first peak, peak force after low position (n = 16). H, bimodal, first peak greater than second peak, peak force before low point (n = 4)

Neither of the unweighting phase metrics differed between above and below average jumps. Of the seven braking phase metrics only countermovement depth did not differ between above and below average jumps. All three propulsive phase metrics and RSI were superior for above average jumps (Table 4): 40% higher peak braking power, 19% higher force at low position, 57% higher braking RFD, 24% shorter braking phase duration, 29% higher eccentric force, 34% greater eccentric stiffness, 22% higher peak propulsive power, 9% shorter propulsive phase duration, 12% higher mean propulsive force, 25% higher RSI (all $P < .01$).

4 | DISCUSSION

Despite the plethora of CMJ force plate studies, and the ubiquity of CMJ force plate assessments in athlete monitoring, scant attention has been given to the shape of the force-time relationship (unimodal or bimodal) and how that shape corresponds to the path of the COM (occurrence of peak force relative to COM low position during the countermovement). The present data show that that the most biomechanically efficient jump is one in which peak force coincides with the low position of the countermovement regardless of whether it is a unimodal or bimodal jump. Peak force occurred at low position in 52% of jumps. These jumps were characterized by greater initial unweighting, a faster braking phase, higher values for all five force metrics in the braking phase and resulted in superior jump height and RSI, despite there being no significant differences in peak propulsive power, mean propulsive force, or propulsive duration. The benefit of peak force coinciding with low position appears to be to optimize countermovement biomechanics. In this regard, the

TABLE 2 Comparison of jump metrics between jumps in which peak force occurred at low position vs jumps in which peak force did not occur at low position (Mean ± SD)

Jump metric	Peak force at low position (n = 52)	Peak force not at low position (n = 48)	*P* value
Unweighting phase metrics			
Unweighting phase duration (s)	0.384 ± 0.133	0.431 ± 0.194	.163
Low force (%BW)	19 ± 13%	32 ± 19%	.001
Braking phase metrics			
Countermovement depth (m)	0.382 ± 0.047	0.365 ± 0.050	.093
Peak braking power (W/kg)	24.2 ± 4.7	17.5 ± 5.5	.001
Force at low position (%BW)	270 ± 26%	233 ± 31%	.001
Braking RFD (%BW/s)	1126 ± 328	771 ± 315	.001
Braking phase duration (s)	0.157 ± 0.025	0.195 ± 0.057	.001
Eccentric force (%BW)	251 ± 32%	201 ± 45%	.001
Eccentric stiffness (kN/m)	5.49 ± 1.36	4.60 ± 1.39	.002
Propulsive phase metrics			
Peak propulsive power (W/kg)	58.3 ± 5.3	58.2 ± 5.4	.936
Propulsive phase duration (s)	0.269 ± 0.027	0.276 ± 0.040	.327
Mean propulsive force (%BW)	213 ± 14%	209 ± 18%	.243
Performance metrics			
Jump height (m)	0.441 ± 0.043	0.424 ± 0.034	.028
RSI (ratio)	0.775 ± 0.115	0.696 ± 0.137	.003

Abbreviations: BW, body weight; RSI, reactive strength index.

TABLE 3 Comparison of jump metrics between bimodal jumps in which the first peak was higher vs jumps in which the second peak was higher (Mean ± SD)

Jump metric	First peak dominant (n = 57)	Second peak dominant (n = 16)	*P* value
Unweighting phase metrics			
Unweighting phase duration (s)	0.399 ± 0.154	0.465 ± 0.269	.212
Low force (%BW)	24 ± 16%	37 ± 20%	.027
Braking phase metrics			
Countermovement depth (m)	0.387 ± 0.046	0.374 ± 0.044	.344
Peak braking power (W/kg)	21.5 ± 5.2	15.3 ± 5.0	.001
Force at low position (%BW)	256 ± 22%	206 ± 29%	.001
Braking RFD (%BW/s)	948 ± 239	519 ± 256	.001
Braking phase duration (s)	0.171 ± 0.027	0.236 ± 0.074	.003
Eccentric force (%BW)	232 ± 32%	168 ± 47%	.001
Eccentric stiffness (kN/m)	4.87 ± 1.02	3.92 ± 1.53	.030
Propulsive phase metrics			
Peak propulsive power (W/kg)	57.4 ± 4.6	58.8 ± 5.8	.365
Propulsive phase duration (s)	0.277 ± 0.021	0.300 ± 0.047	.078
Mean propulsive force (%BW)	208 ± 10%	201 ± 18%	.144
Performance metrics			
Jump height (m)	0.433 ± 0.043	0.426 ± 0.040	.561
RSI (ratio)	0.737 ± 0.113	0.644 ± 0.171	.054

Abbreviations: BW, body weight; RSI, reactive strength index.

countermovement has been modelled as a spring, with eccentric stiffness analogous to compressing the spring.[21,22] In the present study eccentric stiffness was 19% higher for jumps in which peak force occurred at low position and eccentric stiffness was 34% higher for above average jumps.

TABLE 4 Differences in jump metrics between below average and above average jumpers (Mean ± SD)

	Jump height group			
	Below average (n = 19)	**Average (n = 64)**	**Above average (n = 17)**	**ANOVA *P* value**
Unweighting phase metrics				
Unweighting phase duration (s)	0.406 ± 0.148	0.411 ± 0.184	0.389 ± 0.109	.889
Low force (%BW)	33 ± 22%	25 ± 16%	21 ± 14%	.062
Braking phase metrics				
Countermovement depth (m)	0.371 ± 0.038	0.371 ± 0.052	0.388 ± 0.050	.440
Peak braking power (W/kg)	17.9 ± 6.7^{b}	20.8 ± 5.8^{b}	25.0 ± 4.2^{a,c}	.002
Force at low position (%BW)	229 ± 42% ^{a,b}	254 ± 30%^{c}	272 ± 27%^{c}	.001
Braking RFD (%BW/s)	740 ± 372%^{a,b}	965 ± 348%^{c}	1163 ± 366%^{c}	.002
Braking phase duration (s)	0.202 ± 0.063 ^{a,b}	0.173 ± 0.043^{c}	0.154 ± 0.023^{c}	.007
Eccentric force (%BW)	196 ± 57%^{a,b}	229 ± 41%^{c}	252 ± 33%^{c}	.001
Eccentric stiffness (N/m)	4116 ± 1330^{a,b}	5219 ± 1404^{c}	5524 ± 1290^{c}	.004
Propulsive phase metrics				
Peak propulsive power (W/kg)	52.3 ± 1.9^{a,b}	58.6 ± 4.6^{b,c}	63.8 ± 3.2^{a,c}	.001
Propulsive phase duration (s)	0.295 ± 0.041^{a,b}	0.267 ± 0.031^{c}	0.268 ± 0.025^{c}	.004
Mean propulsive force (%BW)	196 ± 11%^{a,b}	213 ± 15%^{c}	220 ± 13%^{c}	.001
Performance metrics				
Jump height (m)	0.381 ± 0.005^{a,b}	0.431 ± 0.022^{b,c}	0.495 ± 0.026^{a,c}	.001
RSI (ratio)	0.651 ± 0.117^{a,b}	0.743 ± 0.132^{c}	0.812 ± 0.090^{c}	.001

Abbreviations: BW, body weight; RSI, reactive strength index.

[a] Significantly different from Average group.

[b] Significantly different from Above Average group.

[c] Significantly different from Below Average group ($P < .05$).

Surprisingly, countermovement depth did not differ between jumps in which peak force occurred at low position vs other jumps (Table 2). In contrast, low force was markedly different between jump types; force at the initiation of unweighting dropped to 19% of body weight for jumps in which peak force occurred at low position vs only 32% of body weight for jumps in which peak force did not occur at low position. Thus, the ability to effectively unweight oneself at the initiation of the jump appears to be more important than countermovement depth in optimizing the timing between eccentric force development and COM countermovement. Consistent with this observation, unweighting has been shown to be impaired on the days after a professional soccer game, while countermovement depth was not.[26]

The majority of CMJs were bimodal (78%). This differs somewhat from a sample of 33 professional rugby players in which only 52% of jumps were bimodal.[27] In both studies jump heights were not different between unimodal and bimodal jumps and both studies found that unimodal jumps had a shallower countermovement, a faster propulsive phase, and a higher mean propulsive force. One notable difference between the studies was that bimodal jumps had greater unweighting in the study of rugby players (10% of body weight vs 18% for unimodal jumps) while in the present study these values were not different between jumps (22% for unimodal, 27% for bimodal). In a small sample of 17 college students performing six CMJs with arms akimbo, 62% had bimodal GRFs[13] but most subjects did not have the same profile for each of the six jumps and the effect on jump metrics was not examined.

It is intuitive that most metrics differed between athletes with above average vs below jump heights even though the study sample was somewhat homogeneous with regard to jump height (inter-subject coefficient of variation 9%) and that athletes were selected for inclusion because they had superior jump heights in comparison to their peers. However, the differences between above and below average jumpers were much greater for braking phase metrics vs propulsive phase metrics. Compared with below average jumpers above average jumpers had 57% greater braking RFD, 40% greater peak braking power, 34% greater eccentric stiffness, 29% greater eccentric force, and a 19% faster braking phase. By contrast, the differences between above and below average jumpers were only 22% for peak propulsive power, 12% for mean propulsive force, and 9% for propulsive duration. Thus, superior jump heights were primarily characterized by having better braking phase mechanics. In line with these findings, greater braking RFD for better jumpers has previously been reported for a sample of 5- to 8-year-old female gymnasts[17] and a sample of 16- to 19-year-old male rugby players.[2] Furthermore, those studies[2,17] and the present study found that better jumpers had a higher force at low position.

A strength of the current study is that it comprised a large sample of high-level athletes across a range of different sports. However, the athletes were selected based on having a higher than average jump height (top 100 in the database of division one college athletes from a single institution). Jump height was calculated using the impulse-momentum method and averaged 0.43 m. This value is higher than impulse-momentum derived values reported for 33 professional rugby players (0.35 m),[27] 22 NCAA division one basketball players (0.36 m),[3] and 26 NCAA division one soccer players (0.37 m).[12] The extent to which the findings reported here apply to athletic populations with lower jump heights is not known.

Most CMJ studies calculate jump height by first calculating vertical velocity at take-off based on the net propulsive impulse (net propulsive impulse/ body mass = take-off velocity). Therefore, net propulsive impulse and jump height are, by definition, the same metric in different units and as such it does not make sense to report net propulsive impulse when jump height is reported. RSI is a more practical metric for assessing athletes than braking or propulsive impulse because impulse is a product of time and practitioners are usually more interested in how quickly an athlete can execute a task. RSI is the ratio of flight time to ground contact time and as a performance metric combines how high the athlete can jump (flight time) with how quickly the athlete can jump (time to get off the ground). It is noteworthy that RSI was higher for jumps in which peak force coincided with low position vs those in which it did not, and for unimodal jumps vs bimodal jumps. Thus, these jumps can be regarded as biomechanically efficient.

It is important to consider that the conclusions in the present study are specific to CMJs without any arm swing. The addition of an arm swing will change the temporal relationships between COM movement and force development through the phases of the jump, and this will alter the force profiles.[4-7] Arm swing CMJs likely involve a greater component of technique while CMJs with no arm swing might be a better approach to studying the utilization of elastic energy in the lower extremities.

The CMJ testing examined in this study was part of the routine monitoring of the athletes and the study sample was selected based on the athletes' superior jump heights. The results point to the importance of peak force occurring at low position as an indicator of biomechanical efficiency. However, the extent to which athletes consistently show the same profile between jumps and between days was not specifically examined. Since the index jump included for analysis in this study was by definition the athlete's best jump there would be no good comparison to see how reproducible the occurrence of peak force at low position was. Among this sample of 100 athletes 92 had a second jump on the same day that was within 10% of their best jump height. All 52 athletes whose best jump was one in which peak force occurred at low position had a second jump within 10% of that jump. Peak force coincided with low position in 42 of these jumps (81%). Considering that the criteria were for force at low position to be within 1% of peak force to be categorized as occurring at low position, 81% reproducibility indicates that this is likely a consistent profile for superior jumps. Forty of the 48 athletes for whom peak force did not occur at low position in their best jump had a second jump on the same day that was within 10% of their best jump height. Twenty-five of these 40 jumps had the same profile (63%) with peak force again not occurring at low position. A study of the reproducibility of jump profiles among athletes is warranted.

The practical implications of these findings remain to be established and would be dependent on the purpose of the CMJ testing. For example, CMJ testing is used to monitor recovery in athletes[26] and it is possible that biomechanical efficiency is impaired when athletes are not fully recovered. Examining the occurrence of peak force relative to low position might be an important practical metric. If the goal of CMJ testing is to assess and improve jump performance an athlete with a biomechanically efficient CMJ might benefit from strength training while an athlete with an inefficient CMJ profile might benefit from improving their jumping technique.

5 | PERSPECTIVES

Vertical jump testing on force plates has become ubiquitous in athlete assessment and screening. To date, the practical relevance of the shape of the CMJ GRF profile and its relationship to COM countermovement has not been considered. The primary practical finding in this study is that jumps in which peak force coincided with low position had superior braking phase metrics that resulted in better jump height and RSI. These jumps optimized the elastic energy generated during the countermovement. Unimodal jumps, and bimodal jumps in which the initial peak exceeded the second peak, also had superior jump metrics, but these effects were not as comprehensive as the benefit of having peak force occur at low position. The optimal profile for CMJ performance is one in which peak force occurs at low position. This provides a qualitative means of identifying biomechanically efficient jumps and should be included in the assessment of CMJ performance.

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REFERENCES

1. Cormack SJ, Newton RU, McGuigan MR, Doyle TL. Reliability of measures obtained during single and repeated countermovement jumps. *Int J Sports Physiol Perform*. 2008;3(2):131-144.
2. Floría P, Gómez-Landero LA, Suárez-Arrones L, et al. Kinetic and kinematic analysis for assessing the differences in countermovement jump performance in rugby players. *J Strength Cond Res*. 2016;30:2533-2539.
3. Heishman AD, Daub BD, Miller RM, et al. Countermovement jump reliability performed with and without an arm swing in NCAA division 1 intercollegiate basketball players. *J Strength Cond Res*. 2020;34:546-558.
4. Feltner ME, Bishop EJ, Perez CM. Segmental and kinetic contributions in vertical jumps performed with and without an arm swing. *Res Q Exercise Sport*. 2004;75:216-230.
5. Gillen ZM, Shoemaker ME, McKay BD, Bohannon NA, Gibson SM, Cramer JT. Influences of the stretch-shortening cycle and arm swing on vertical jump performance in children and adolescents. *J Strength Cond Res*. 2020. https://doi.org/10.1519/JSC.0000000000003647
6. Hara M, Shibayama A, Takeshita D, Fukashiro S. The effect of arm swing on lower extremities in vertical jumping. *J Biomech*. 2006;39(13):2503-2511.
7. Lees A, Vanrenterghem J, De Clercq D. Understanding how an arm swing enhances performance in the vertical jump. *J Biomech*. 2004;37(12):1929-1940.
8. Aboodarda SJ, Yusof A, Osman NA, Thompson MW, Mokhtar AH. Enhanced performance with elastic resistance during the eccentric phase of a countermovement jump. *Int J of Sport Physiol*. 2013;8:181-187.
9. Heishman A, Daub B, Miller R, et al. Countermovement jump inter-limb asymmetries in collegiate basketball players. *Sports*. 2019;7:103.
10. Pinto BL, McGill SM. Voluntary muscle relaxation can mitigate fatigue and improve countermovement jump performance. *J Strength Cond Res*. 2020;34:1525-1529.
11. Harper DJ, Cohen DD, Carling C, Kiely J. Can countermovement jump neuromuscular performance qualities differentiate maximal horizontal deceleration ability in team sport athletes? *Sports*. 2020;8(6):76.
12. Barker LA, Harry JR, Mercer JA. Relationships between countermovement jump ground reaction forces and jump height, reactive strength index, and jump time. *J Strength Cond Res*. 2018;32:248-254.
13. Pérez-Castilla A, Rojas FJ, Gómez-Martínez F, García-Ramos A. Vertical jump performance is affected by the velocity and depth of the countermovement. *Sport Biomech*. 2019;31:1-6.
14. Bobbert MF, Casius LJ. Is the effect of a countermovement on jump height due to active state development? *Med Sci Sport Exer*. 2005;37:440-446.
15. Bobbert MF, Huijing PA. Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Med Sci Sport Exer*. 1987;19:332-338.
16. Bojsen-Møller J, Magnusson SP, Rasmussen LR, et al. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. *J Appl Physiol*. 2005;99:986-994.
17. Floría P, Harrison AJ. Ground reaction force differences in the countermovement jump in girls with different levels of performance. *Res Q Exerc Sport*. 2013;84:329-335.
18. Jordan MJ, Aagaard P, Herzog W. Lower limb asymmetry in mechanical muscle function: a comparison between ski racers with and without ACL reconstruction. *Scand J Med Sci Sports*. 2015;25(3):e301–9.
19. Miles JJ, King E, Falvey ÉC, Daniels KAJ. Patellar and hamstring autografts are associated with different jump task loading asymmetries after ACL reconstruction. *Scand J Med Sci Sports*. 2019;29(8):1212-1222.
20. Mina MA, Blazevich AJ, Tsatalas T, Giakas G, Seitz LB, Kay AD. Variable, but not free-weight, resistance back squat exercise potentiates jump performance following a comprehensive task-specific warm-up. *Scand J Med Sci Sports*. 2019;29(3):380-392.
21. Struzik A, Zawadzki J. Estimation of potential elastic energy during the countermovement phase of a vertical jump based on the force-displacement curve. *Acta Bioeng Biomech*. 2019;21:153-160.
22. Struzik A, Zawadzki J. Leg stiffness during phases of countermovement and take-off in vertical jump. *Acta Bioeng Biomech*. 2013;15:113-118.
23. Hoffren M, Ishikawa M, Komi PV. Age-related neuromuscular function during drop jumps. *J Appl Physiol*. 2007;103:1276-1283.
24. Ishikawa M, Komi PV. Effects of different dropping intensities on fascicle and tendinous tissue behavior during stretch-shortening cycle exercise. *J Appl Physiol*. 2004;96:848-852.
25. Sousa F, Ishikawa M, Vilas-Boas JP, Komi PV. Intensity-and muscle-specific fascicle behavior during human drop jumps. *J Appl Physiol*. 2007;102:382-389.
26. McHugh MP, Clifford T, Abbott W, et al. Countermovement jump recovery in professional soccer players using an inertial sensor. *Int J of Sport Physiol*. 2019;14:9-15.
27. Kennedy R, Drake D. Is a bimodal force-time curve related to countermovement jump performance? *Sports*. 2018;6:36.

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