PREDICTING MAXIMAL COUNTERMOVEMENT JUMP HEIGHT FROM UPRIGHT AND SQUAT POSITIONS

HEAD TITLE: UPRIGHT AND SQUAT MAXIMUM JUMP HEIGHT PREDICTORS

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ABSTRACT

Introduction. Countermovement jump is common in sport and testing and performed from various starting positions. Little is known about effective contributors to maximal countermovement jump height from various starting positions.

Purpose and Objectives. Determine effective jump height predictors and effect of starting position on countermovement jump height.

Applied Methodology. Forty-nine collegiate athletes performed maximal height countermovement jumps from upright and squatting positions with arm movement. Several variables were calculated from kinetic data. Correlation and regression determined variables related to and predictive of jump height in both conditions. Paired t-tests evaluated differences in jump height.

Achieved Major Results. Upright condition jump height positively correlated with peak force and power, eccentric and concentric impulses, and countermovement depth. Jump height prediction included peak force and power, and eccentric and concentric impulses. Squat condition jump height positively correlated with peak force and power, mean rate of force development, force generated at the beginning of propulsion, and concentric impulse. Jump height prediction equation included mean rate of force development, force at the beginning of propulsion, and peak power. Jump height was higher in the upright condition.

Conclusions. Higher jumps are achieved from the upright position. Peak force, peak power, and concentric and eccentric impulses best contribute to upright jump height. Mean rate of force development, force at the beginning of propulsion, and peak power best predicted squat jump height.

Limitations. We did not restrict arm movement, to encourage natural motion. Depth was not controlled, rather advising a comfortable depth. Subjects were recruited from various collegiate sports.

Practical implications. Maximal jump height from various positions may be achieved through efforts to maximize jump peak power and increase musculotendinous loading in sport-specific starting positions.

Originality/Value. This is the first study to explore the predictors of upright and squat countermovement jumps. These results can guide jump performance training.

Keywords: *Impulse, Countermovement, Peak Force, Peak Power, Starting Position*

Submitted: 10 October 2021
Revised: 19 November 2021
Accepted: 2 December 2021

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Cite this article as:
Suprak, D., Amasay, T. (2021). Predicting maximal countermovement jump height from upright and squat positions *Journal of Applied Sports Sciences*, Vol.2, pp. 3-16.
DOI: *10.37393/JASS.2021.02.1*

INTRODUCTION

A countermovement jump (CMJ) is an explosive jump comprised of a preliminary downward motion followed by an upward motion, accelerating the center of mass vertically. This maneuver is common both in activities of daily living, as well as in many sporting environments, and takes advantage of the stretch-shortening cycle (SSC). The SSC combines the eccentric (lengthening) and concentric (shortening) actions of an agonist muscle to capitalize on the force generation from both the stretch reflex and stored elastic energy in the tendon to maximize force output at the beginning of the concentric phase, as well as increased crossbridge formation during the eccentric phase (Cormie et al., 2010), resulting in production of net vertical impulse at a higher rate and shorter amount of time (Guess et al., 2020). The potential of the SSC to result in maximum force output during the concentric phase depends on range of muscle lengthening, as well as shortening velocity and acceleration (Cormie et al., 2010, Mandic et al., 2015). In addition, a countermovement may allow for development of a higher level of muscle active state, resulting in greater joint moments at the start of the concentric phase (Bobbert et al., 1996).

The CMJ is used extensively as a simple test that lends insight into the neuromuscular and SSC capabilities of the lower extremity. As such, much work has been done to examine variables related to CMJ execution and their contribution to jump performance and efficiency. CMJ performance is often assessed using 3D camera systems and force platforms, specifically examining the vertical ground reaction forces (vGRF) to derive the force-time curve, and numerous related variables. Such research has demonstrated the countermovement depth (Perez-Castilla et al., 2019, Sanchez-Sixto et al., 2018), rate of force development in the eccentric phase (ERFD) (Barker et al., 2018, Laffaye & Wagner, 2013), eccentric phase impulse (Sole et al., 2018), peak force (Daugherty et al., 2021, Dowling & Vamos, 1993), peak rate of force development (RFD) (McLellan et al., 2011), and peak power (Barker et al., 2018, Daugherty et al., 2021, Dowling & Vamos, 1993, Harman et al., 1991) during the jump are all positively related to maximal jump height.

In sports, athletes often begin explosive movements, such as countermovement jumps, from various positions, depending on the situation. Previously, Amasay (2008) reported greater maximal jump height when starting from the upright, compared to a self-selected squat, position in a maximal height block jump in collegiate volleyball players. However, little is known regarding the relative importance of factors contributing to success in CMJs performed for

maximal jump height (JH) from upright and squat starting positions. Therefore, the purpose of this study was to use a bivariate correlation and multiple regression approach to determine effective predictors of JH in CMJs performed for maximal height from both upright and squat positions. A secondary purpose was to determine the effects of starting position (upright vs. squat) on JH in a CMJ performed for maximal height. The knowledge gained could be helpful in designing targeted training programs for improving JH and lower extremity explosive performance. In accordance with previous research, we hypothesized that variables related to force generation (peak force, rates of force development, and impulse), peak power, and countermovement depth would exhibit greater correlations with, and be more predictive of, JH than other variables. We also hypothesized that variables related to the eccentric phase of

CMJ would be more predictive of JH in the upright, compared to the squat, starting position. Further, we hypothesized greater JH from the upright versus the squat starting position.

METHODOLOGY

Ethical Statement

The university institutional review board approved the study in accordance with the Helsinki Declaration. All subjects read and signed an informed consent form prior to data collection.

Subjects

Forty-nine Division II athletes (22 males, 27 females) participated in the study. Subject demographics are presented in table 1. The athletes participating in the study were from different collegiate varsity teams including soccer, basketball, tennis, rowing, softball and baseball. All subjects were free of acute injuries prior to the testing and cleared by the university sports medicine staff to participate in their team training and this study without limitations.

Table 1. *Subject demographics.*

	Age (yrs)	Height (cm)	Weight (kg)	College Experience (yrs)	Total Experience (yrs)
Group Mean (SD)	20.2 (1.5)	175.3 (8.6)	73.8 (10.6)	2.8 (1.2)	11.0 (4.6)
Women Mean (SD)	20.4 (1.4)	171.5 (8.2)	67.8 (7.4)	2.9 (1.2)	8.7 (4.6)
Men Mean (SD)	20.0 (1.5)	179.9 (6.6)	81.2 (9.1)	2.7 (1.2)	13.7 (2.7)

Procedure

All data were collected in a single session. Subjects performed a 10-minute general and specific dynamic warm-up before testing began. The general warm-up consisted of riding a stationary bike at a self-selected pace. The specific warm-up consisted of high knees, heel to toes, marching, squats, front lunges, carioca, and submaximal vertical jumps.

Kinetic data were collected using two adjacent in-ground AMTI OR6-6 force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) sampled at 960 Hz, and Vicon Nexus 1.7.1 software (Vicon, Centennial, CO, USA). Data were filtered via a fourth order Butterworth low-pass filter with a cutoff frequency of 300 Hz.

Subjects' body weight was calculated using the summed vGRF from the force plates during a standing trial. Each subject stood on the force plates for at least 3 seconds. The vGRF from each force plate recorded over middle second was averaged while the subject stood motionless and the data from the two force plates were summed to calculate subjects' body weight in newtons.

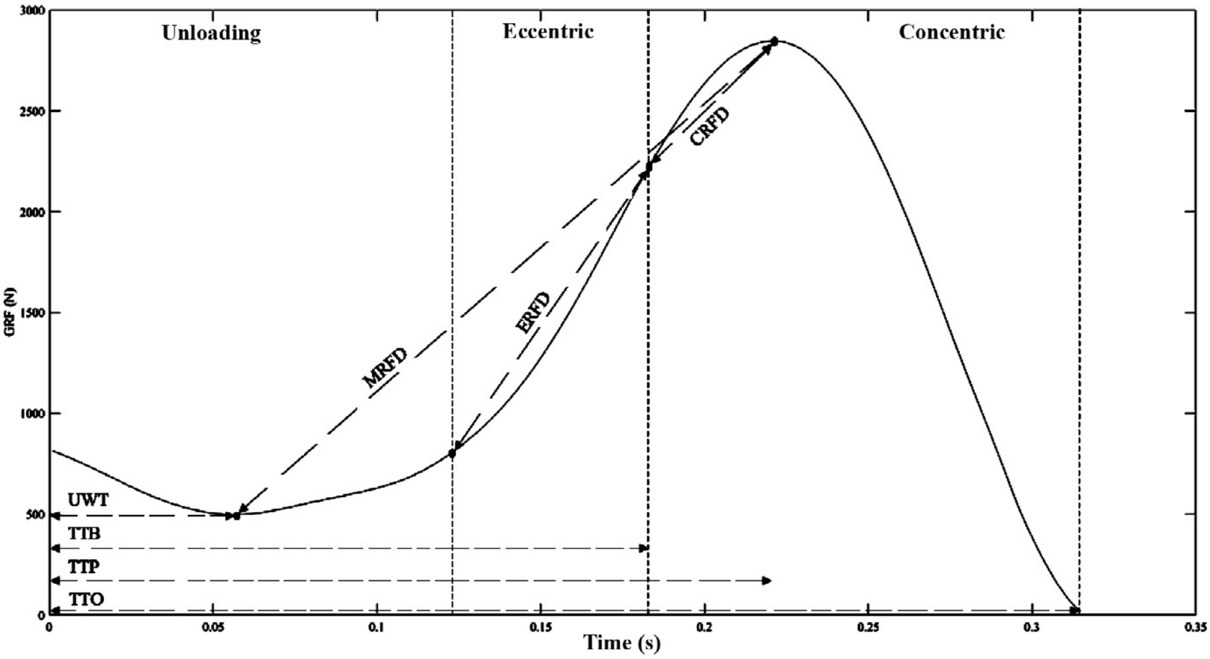
Following the warm-up, subjects performed three maximal height CMJs from the upright starting position and three maximal height CMJs from a squat starting position, separated by at least two minutes of rest. Subjects were positioned with one foot on each force plate, and a Vertec (Sports Imports, Columbus, OH, USA) positioned as a target so subjects could jump vertically and touch its vanes. For the upright maximal CMJs, subjects began by standing in a comfortable upright position. Subjects were instructed to perform a rapid countermovement to a self-selected depth and immediately jump vertically with maximal effort. Subjects were required to land with both feet on the force plates on which they began, or jumps were repeated. The maximal CMJ from the squat position was performed identically to the upright jump but beginning from a self-selected squatting position. Subjects were instructed to assume a self-selected squat position, similar to the starting position they would adopt when playing their sport. As with the upright condition, subjects were instructed to perform a rapid countermovement to a self-selected depth and immediately jump vertically with maximal effort. Arm movement was not restricted during jumps. The jump with the highest center of mass (COM) vertical displacement of the three jumps, from each starting position, calculated from the kinetic data was taken as their maximal vertical jump. Kinetic data were used for all subsequent calculations.

Data were analyzed via custom written Matlab R2020 software (Mathworks, Natick, MA). The start of the countermovement was identified when the vGRF was above or below the body weight by more than 2.5% of body weight (Barker et al., 2018), and stayed for at least 50 data points. Toe-off was identified when the vGRF dropped below 20 N (Barker et al., 2018), and stayed for at least 100 data points. Vertical COM velocity at take-off was calculated as the integration of COM acceleration (a = (vGRF – body weight)/mass). JH was then calculated from COM velocity with the equation in Table 2. The trial with the highest JH was analyzed for each subject for each starting position. Fifteen variables were calculated for each jump, based on the kinetic data collected: JH (m), eccentric rate of force development (ERFD) (N/s), concentric rate of force development (CRFD) (N/s), mean rate of force development (MRFD) (N/s), peak RFD (PRFD) (N/s), force at the bottom of the countermovement (FAB) (N), peak force (PF) (N), unweighting time (UWT) (s), time to bottom of the countermovement (TTB) (s), time to peak force (TTP) (s), time to take-off (TTO) (s), eccentric Impulse (EccImp) (Ns), concentric impulse (ConImp) (Ns), peak power (PP) (W/kg), and COM displacement during the countermovement (CMDepth) (m). The formulas for each of these variables are shown in Table 2. An illustration of the phases of the CMJ, RFDs and times calculated in this study is presented in Figure 1.

Table 2. *Variable calculation formulas.*

Variable	Formula
Jump height (JH) (m)	$\mathrm{JH} = \frac{\mathrm{COM}\ \mathit{takeoff\ velocity}^2}{2*9.81\mathrm{m/s}^2}$ COM velocity calculated as integration of acceleration of the COM
Peak force (PF) (N)	Maximal vertical GRF during jump
Countermovement depth (CM-Depth) (m)	Difference in COM height between starting position and bottom of the countermovement. Calculated as double integration of acceleration of the COM. Divides the eccentric (countermovement) and concentric (propulsive) phases.

Force at bottom of the countermovement (FAB) (N)	Vertical GRF at point where COM reaches the maximum negative displacement.
Eccentric rate of force development (ERFD) (N/s)	$\mathrm{ERFD} = \frac{\textit{FAB-Force at beginning of eccentric phase}}{\textit{change in time}}$
Concentric rate of force development (CRFD) (N/s)	$\mathrm{CRFD} = \frac{\textit{Peak force - Force at bottom of countermovement}}{\textit{change in time}}$
Mean rate of force development (MRFD) (N/s)	$\mathrm{MRFD} = \frac{\text{Peak force-minimum force}}{\textit{change in time}}$
Peak rate of force development (PRFD) (N/s)	Maximum positive slope of vertical GRF over 10-ms intervals
Unweight time (UWT) (s)	Elapsed time from beginning of the jump to the minimum vertical GRF
Time to bottom of countermovement (TTB) (s)	Elapsed time from beginning of the jump to the maximal negative COM displacement
Time to peak force (TTP) (s)	Elapsed time from beginning of the jump to the maximal vertical GRF
Time to take-off (TTO) (s)	Elapsed time from beginning of the jump to the instant of toe-off, when the subject left the ground
Eccentric impulse (EccImp) (Ns)	The area under the GRF-time curve during the eccentric (countermovement) phase
Concentric impulse (ConImp) (Ns)	The area under the GRF-time curve during the concentric (propulsive) phase
Peak Power Output (PP) (W/kg)	Maximal product of vertical GRF and COM velocity during the jump, normalized to body mass



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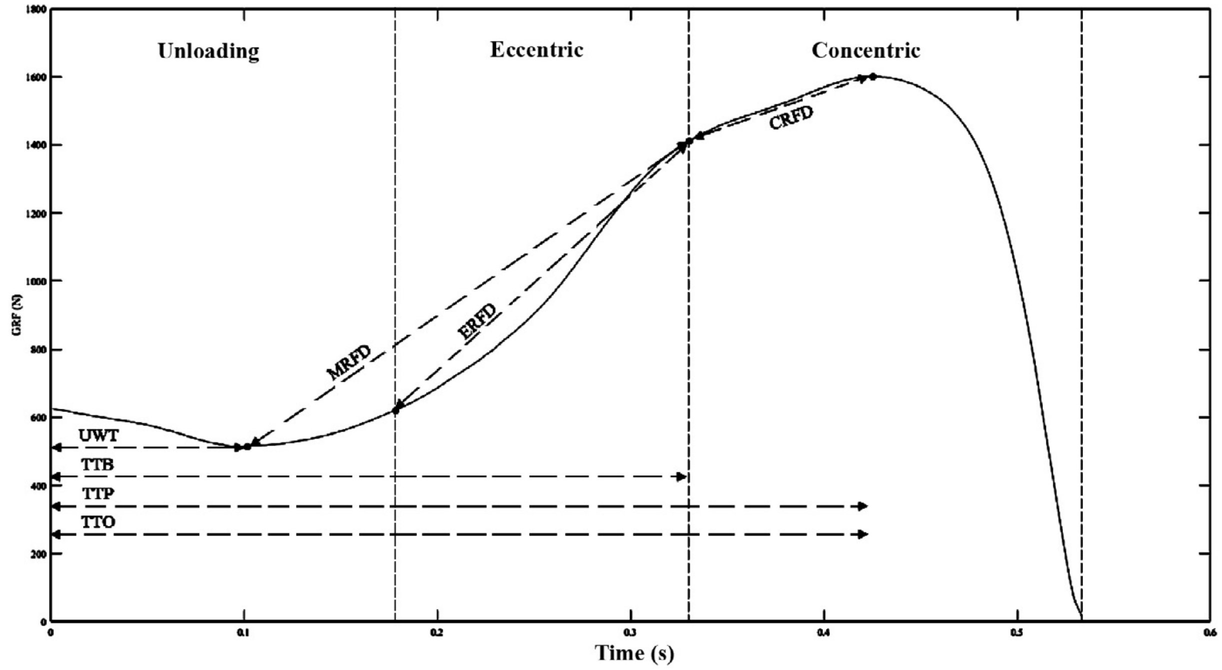

b)

Figure 1. *Illustration of jump phases and RFD calculations for a. upright and b. squat CMJ conditions*

Statistical Analysis

IBM SPSS Statistics Version 28 was used for statistical analyses. A priori power analysis was conducted using pilot data. Based on this pilot data and using the resulting adjusted multiple correlation of r = .918, fourteen predictor variables (ERFD, CRFD, MRFD, PRFD, FAB, PF, UWT, TTB, TTP, TTO, EcclImp, ConImp, PP, and CMDepth), and an alpha level of $p < .05$, at least 20 subjects would be required to obtain a power level of 0.8. In addition, the power analysis for the t-test based upon a comparison of JH in CMJ and squat jump revealed that with an estimated effect size of d = 0.488 (Wadhi et al., 2018), at least 35 subjects would be required to achieve a power level of 0.8 at an alpha level of $p < .05$.

Histograms were examined to assess the assumption of normality for each variable. The Shapiro-Wilk test was used to assess normality of JH for each condition. Linearity between predictor variables and JH were assessed using bivariate scatterplots. Pearson correlation coefficients were calculated between each calculated variable and JH, and their strength was evaluated using benchmarks outlined by Field (2018). Correlation coefficients less than 0.2 were classified as weak, those between 0.2 – 0.49 were moderate, and those 0.5 and above were strong.

Only significant correlations were used to identify predictor variables to include in the regression analysis. Multicollinearity was evaluated via the variance inflation factor (VIF) for each predictor variable. In the case that two or more predictors exhibited a VIF greater than 10 (Field, 2018), the predictor with the highest bivariate correlation with the JH was kept in the model, while the other predictor was discarded. Once appropriate predictors were identified, they were entered into a backward stepwise multiple regression, with a t-test exit criterion of $p > .1$ (Laffaye & Wagner, 2013). The analysis of variance (ANOVA) and adjusted R^2 were used to evaluate goodness of fit for the resulting regression models for upright and squat conditions.

Paired t-tests were conducted to compare JH across upright and squat conditions. The alpha level was set at $p < .05$. Cohen's *d* was used to evaluate effect sizes for these comparisons, according to the benchmarks of small (0.2), medium (0.5), and large (0.8) effects (Cohen, 1988).

RESULTS

Upright Max Jump Regression Results

Table 3 shows mean (± SD) values for each variable calculated in the upright and squat conditions. The Shapiro-Wilk test indicated that data for JH in the upright condition were normally distributed ($p = .15$). All predictor variables were normally distributed and linearly related to JH, based on examination of histograms and bivariate scatterplots, respectively. Several variables exhibited significant correlations with JH (Table 4). PF, EccImp, ConImp, and PP were all strongly correlated with JH. FAB and CMDepth showed moderate correlations with JH. No weak correlations were found to be significant.

Table 3. *Variable mean (± SD) by condition.*

	Upright	**Squat**
Jump Height (m)	0.391 (0.116)	0.383 (0.118)
ERFD (N/s)	6060.43 (8152.29)	5623.78 (3600.93)
CRFD (N/s)	1518.54 (2182.51)	3023.40 (2629.76)
MRFD (N/s)	3948.69 (3113.68)	3691.16 (1910.11)
PRFD (N/s)	12,509.66 (14,162.24)	11,193.12 (6528.94)
FAB (N)	1566.91 (326.06)	1230.22 (380.11)
PF (N)	1842.71 (325.34)	1794.25 (369.27)
UWT (s)	0.422 (0.348)	0.493 (0.355)
TTB (s)	0.753 (0.350)	0.689 (0.364)
TTP (s)	0.903 (0.359)	0.902 (0.387)
TTO (s)	1.05 (0.362)	1.01 (0.385)
RSIMod (m/s)	0.397 (0.148)	0.436 (0.238)
EccImp (Ns)	77.18 (24.88)	26.79 (22.44)
ConImp (Ns)	211.98 (53.72)	205.69 (51.78)
PP (W/kg)	56.56 (12.93)	55.93 (13.06)
CMDepth (m)	0.279 (0.085)	0.014 (0.098)

Variables with significant correlations with JH were entered into the backward stepwise multiple regression analysis. After excluding variables with non-significant t-values, or with VIF greater than 10, the variables that remained in the regression model were PF, EccImp, ConImp, and PP ($F[4, 44] = 481.42$, $p < .001$, adjusted $R^2 = .976$). These variables significantly predicted JH with the equation:

Jump Height = -.056 – 0.00013(PF) + 0.001(EccImp) + .001(ConImp) + 0.008(PP).

Table 4. *Pearson's correlation coefficient for each variable with JH in the upright starting position.*

	ERFD	CRFD	MRFD	PRFD	FAB	PF	UWT	TTB	TTP	TTO	EccImp	ConImp	PP	CMDepth
JH	-.036	.078	.028	.040	.440*	.641*	.257	.266	.273	.256	.555*	.797*	.960*	.487*

**Denotes significance (p < .05).*

Squat Max Jump Regression Results

The Shapiro-Wilk test indicated that data for JH in the squat condition were normally distributed ($p = .197$). Histograms and bivariate scatterplots demonstrated that all predictor variables were normally distributed and linearly related to JH. As with the upright max results, several variables in the squat max jump were significantly correlated with JH (Table 5). PF, ConImp, and PP were all strongly correlated with JH. Variables with moderate significant correlations to JH included MRFD and FAB. No weak correlations were significant. The variables with significant correlations with JH were entered into the backward stepwise multiple regression analysis. After excluding variables with non-significant t-values, or with VIF greater than 10, the variables that remained in the regression model were MRFD, FAB, and PP. This model significantly predicted JH ($F[3, 45] = 332.50$, $p < .001$, adjusted $R^2 = .954$). The resulting prediction equation was JH = - 0.197 - .00001(MRFD) + .000021(FAB) + .009(PP).

Table 5. *Pearson's correlation coefficient for each variable with JH in the squat starting position.*

	ERFD	CRFD	MRFD	PRFD	FAB	PF	UWT	TTB	TTP	TTO	EccImp	ConImp	PP	CMDepth
JH	.269	.224	.305*	.226	.329*	.657*	.158	.097	.101	.092	.259	.843*	.969*	.037

**Denotes significance (p < .05).*

Upright vs. Squat Condition Comparison

Paired t-tests indicated JH was significantly higher in the upright, compared to the squat, max jump condition ($t(48) = 2.54$, $p = .014$). However, the mean difference between conditions was small (0.0086 m), with a small effect size ($d = .363$).

DISCUSSION

The primary purpose of this study was to use a bivariate correlation and multiple regression approach to determine the most effective predictors of JH in a CMJ performed for maximal height from both upright and squat starting positions. We hypothesized that variables related to force generation, countermovement depth, and PP would exhibit greater correlations, and be more predictive of, JH than others. Our hypothesis was partially supported, since the variables exhibiting significant correlations with JH in the upright condition included PF, PP, EccImp, FAB, ConImp, and CMDepth. This result was expected, since previous authors have reported significant positive correlations between JH and PF (Daugherty et al., 2021, Dowling & Vamos, 1993), PP (Barker et al., 2018, Daugherty et al., 2021, Dowling & Vamos, 1993, Harman et al., 1991), CMDepth (Perez-Castilla et al., 2019, Pérez-Castilla et al., 2020, Salles et al., 2011, Sanchez-Sixto et al., 2018), and EccImp (Sole et al., 2018).

One unexpected result was that ERFD did not show a significant correlation to JH, which contrasts with previous findings (Barker et al., 2018, Laffaye & Wagner, 2013). However, this discrepancy may be due to a difference in the definition of the eccentric phase between these reports and the current study. In both of these previous works, the authors defined the beginning of the eccentric phase as the point of minimum GRF (maximum unweighting), whereas in the current study, we defined it as the point of maximum downward velocity of the COM (corresponding to the point when GRF returns to body weight), in accordance with other more recent works (Sahrom et al., 2020, Sole et al., 2018). This difference in the definition of the start of the eccentric phase may contribute to a difference in the calculation of ERFD, and therefore, the difference in findings here.

The variables that best predicted JH from the upright position in the resulting regression model included PF, PP, EccImp, and ConImp. According to the present results, FAB was strongly significantly correlated with PF (r = .769, p > .001), ERFD (r = .549, p < .001), EccImp (r = .503, p < .001), and ConImp (r = .681, p < .001). In addition, FAB was moderately correlated with PP (r = .442, p = .001). Therefore, it may be that, although we did not find a correlation between ERFD and JH, greater ERFD and EccImp are related to higher FAB, which may contribute to greater ConImp and PF, and thereby, higher JH. In other words, rapid force development in the eccentric phase (ERFD) may result in large accumulation of force during this phase (EcсImp), and therefore, a higher force at the end of this phase and beginning of the concentric phase (FAB). In addition, higher force developed at the beginning of propulsion (FAB) may lead to higher PP, and therefore, a higher JH. Indeed, rapid eccentric muscle action immediately prior to concentric action results in residual force enhancement from intramuscular proteins and tendon stretch, and thereby, greater force at the beginning of propulsion as well as elevated force and power in the concentric phase of a stretch-shortening cycle (Fukutani et al., 2017), such as a CMJ. Efforts to improve lower extremity explosive performance and JH from the upright position may, thus, benefit from a focus on maximizing the rate of and total force generation during the eccentric phase of the SSC, as well as maximum force generation capacity.

In a maximum height jump from the squat starting position, the current data indicated strong positive correlations of PF, ConImp, and PP with JH. Moderate positive correlations with JH were found for MRFD and FAB. Therefore, increasing FAB, MRFD, ConImp, PF, and PP are associated with higher JH from a squat starting position. It is not surprising that neither EccImp nor CMDepth were significantly associated with JH from the squat position, as they were in the upright position, since CMDepth, and thus the eccentric phase, was much smaller in the squat condition (0.279 m in upright vs. 0.014 m in squat). This finding agrees with our hypothesis.

The significant regression model predicting JH in the squat starting position included only the variables MRFD, FAB, and PP. So, our hypothesis was only partially supported regarding the squat condition, since the regression equation retained some of the force-related variables, but not others. This model suggests that JH is maximized in a situation in which rapid generation of force after unweighting (MRFD) and high force generation at the beginning of propulsion results in high maximum power output, and ultimately higher JH. Further examination of these variables reveals that MRFD was strongly correlated to PRFD ($r = .861$, $p < .001$) and PF ($r = .651$, $p < .001$). This illustrates the importance of rapid force production to generate high maximum force, especially when the eccentric phase is short. FAB was strongly related to ERFD ($r = .792$, $p < .001$) and EccImp ($r = .876$, $p < .001$). So, although ERFD and EccImp were not significantly related to JH when the eccentric phase was short, this finding still shows the importance of rapid force development to generate high average eccentric force and begin propulsion at a high force. According to the current results, PP was strongly related to ConImp ($r = .813$, $p < .001$). Therefore, generating a high average force during the concentric phase of a CMJ from the squat position appears to contribute to high PP, and thereby, JH. These results may indicate that improvements in JH from the squat starting position may be achieved through efforts to increase capacity for rapid force development and generating high force at the beginning of the concentric propulsive phase, as well as improving the force generation during the concentric phase to maximize PP.

In the upright condition, both FAB ($r = .44$) and CMDepth ($r = .487$) were significantly and moderately correlated with JH. Examination of their coefficients of determination reveals that variation in FAB and CMDepth account for 19% and 24% of the variation in JH, respectively. In the squat condition, MRFD ($r = .305$) and FAB ($r = .329$) were significantly and moderately correlated with JH. Examination of their coefficients of determination reveals that variation in MRFD and FAB can explain 9% and 11% of the variation in JH, respectively. Therefore, by themselves, each of these variables doesn't predict a large portion of the variability in JH, but when entered into the regression analysis for the condition, they contribute significantly to the prediction equation of JH, as indicated by the t-value associated with each variable in the regression analysis. Therefore, we believe that these variables should be considered in the prediction of JH in their respective conditions.

Our secondary purpose was to determine the effects of starting position (upright vs.

squat) on JH in a CMJ performed for maximal height. We hypothesized greater JH from the upright versus the squat starting position. Our hypothesis was supported in that JH was shown to be higher in the upright, compared to the squat, max jump condition. Given that the CMDepth was larger in the upright versus the squat condition, this result is supported by findings from other authors. Previous authors have reported that greater countermovement depth resulted in greater net vertical impulse, greater downward and upward COM velocity, increased peak hip, knee, and ankle joint torques, and higher jump height (Salles et al., 2011, Sanchez-Sixto et al., 2018). So, although a squat starting position provides the advantage of a shorter TTO (Mandic et al., 2016), it results in a lower maximum JH. However, the difference in JH between conditions was small (0.0086 m) and may be practically inconsequential.

LIMITATIONS

This investigation had several limitations. First, we did not restrict arm movement during data jumping trials. Although restricting arm movement can isolate the contribution of the lower extremity to the jump, we felt that doing so may alter kinematics of the lower extremity, and that the results would be more applicable to sport performance if arm movement was unrestricted.

We did not control neither the depth of the countermovement in the upright condition, nor the starting position in the squat condition. Subjects were instructed to use the same countermovement or starting squat position they normally would adopt in their sport. We felt that this instruction, without dictating the movement, would result in a more natural and sport-specific movement pattern, and the best result. Future studies should assess the position at bottom of the countermovement.

Our sample of collegiate varsity athletes were taken from several different sports, including soccer, basketball, tennis, rowing, softball and baseball. These sports involve varying demands for jumping and explosive lower extremity movements. Our subjects may have had heterogenous skill levels in the movements performed, and this may have affected the results obtained.

CONCLUSION

The force-time derived variables related to, and predictive of JH are different between CMJ performed from the upright and squat starting positions. In the upright condition, the current data indicated that increasing countermovement depth, eccentric phase impulse, and force generated at the beginning of propulsion, as well as increasing concentric phase impulse, peak force and peak power, were all associated with higher JH. The JH prediction in the upright condition involved variables PF, PP, EccImp, and ConImp. Because FAB was related to PF, ERFD, EccImp, ConImp, efforts aimed at maximizing the rate of and total force generation during the eccentric phase of the SSC, as well as maximum force generation capacity, may help to optimize the impulse generated in the concentric phase and maximize the JH.

In the squat condition, increasing FAB, MRFD, ConImp, PF, and PP are associated with higher JH. The variables that best predicted JH were MRFD, FAB, and PP. These results highlight the importance of methods to increase capacity for developing rapid force and generating high force at the beginning of the concentric propulsive phase, as well as improving the force generation during the concentric phase to maximize PP to maximize JH from a squat starting position. The only variable that helped predict JH in both upright and squat starting positions was PP. Thus, in training to improve performance for sports or activities involving maximum height jumping from a variety of starting positions, it may be beneficial to focus on strategies to maximize PP during the jump, including explosive resistance training (Zemkova et al., 2014), Olympic weightlifting movements (MacKenzie et al., 2014), and plyometrics (Ozbar et al., 2014).

Maximum JH was lower in the squat condition. Coaches and trainers may employ strategies to increase lower extremity musculotendinous loading (and thereby, FAB) in athletes in their starting positions to maximize JH.

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