EFFECTS OF MAXIMAL STRENGTH ON GROUND REACTION FORCE PATTERNS DURING COUNTERMOVEMENT JUMPS

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The purpose of this study was to determine the effects of maximal strength on ground reaction force (GRF) patterns during countermovement jumps (CMJ). Nineteen female lacrosse players performed CMJ and isometric mid-thigh pulls (IMTP) on force plates. Principal components analysis was used on the CMJ time series data to extract GRF patterns. Maximum GRF during the IMTP were extracted and used as a measure of maximal strength. Spearman's rho correlations were used to analyse the relationship between maximal strength and GRF patterns during the CMJ. Results suggest that maximal strength is positively correlated to a GRF CMJ pattern characterised by greater rate of force development and peak force as well as less of a decrease in GRF immediately after the end of the eccentric phase (i.e., absence of bimodal GRF profile).

KEYWORDS: biomechanics, principal components analysis, jumping

INTRODUCTION: The importance of maximal strength for athletic performance is well-established (Suchomel et al., 2016). In addition, previous literature suggests that isometric maximal strength is often related to various discrete performance parameters during athletic tasks, such as the countermovement jump (CMJ) (Thomas et al., 2015). One assessment, the isometric mid-thigh pull (IMTP), is often used as a valid and reliable test of maximal strength as the positioning of the pull closely replicates what is seen during dynamic triple extension movements like the CMJ (Brady et al., 2020). However, making inferences based on discrete variables extracted from time series data may limit insights into the mechanisms or influence of maximal strength on dynamic performance because discrete variables often neglect temporal events or the time-varying patterns during dynamic movements. Thus, important biomechanical information relevant to performance may be lost.

While previous research showed that training status and sport influences the shape of CMJ force-time curves (Cormie et al., 2009; Parker & Lundgren, 2018), there is a paucity of knowledge about how isometric maximal strength influences ground reaction force (GRF) patterns during CMJ, especially among female athletes. Temporal phase analysis (TPA) has been used to explore differences in kinetic and kinematic variables throughout CMJ (Cormie et al., 2009; McMahon et al., 2017), but this analysis still uses discrete time points to make comparisons of GRF time-series. In addition, this analysis could be problematic if combining data from trials that include both unimodal and bimodal shaped GRF curves (Kennedy & Drake, 2018). Rather than selecting time-specific events, principal components analysis (PCA) is an alternative method of data reduction that facilitates a better understanding of the dynamics of time series data (Ramsay & Silverman, 2010). Conducting a PCA of dynamic tasks like the CMJ allows for extraction of common sources of variation within the force-time curves and provides valuable insight into GRF patterns. If these patterns relate to isometric maximal strength, practitioners would be better informed about the relationship between strength capacities and movement characteristics during jumping tasks. Therefore, the purpose of this study is to determine the effects of maximal strength on GRF patterns during the CMJ in female collegiate athletes.

METHODS: Nineteen female lacrosse athletes (Age: 19.5 ± 1.2 yrs; Body Mass: 69.95 ± 9.43 kg; Height: 166.80 ± 4.10 cm) volunteered for this study. Data collection occurred at the beginning of an offseason training period and testing for each athlete was completed within one session. All players participated in a yearly training program that included dynamic and isometric exercises. The study was approved by Marquette University's Institutional Review Board and all players provided written informed consent.

Upon arrival for testing, players performed a standardized dynamic warm-up that included basic callisthenic exercises. Participants then performed two submaximal CMJ before performing up to three maximal effort CMJ, all without arm swing, followed by two submaximal effort IMTP and three maximal effort IMTP with participants were positioned based on recommendations set forth by Comfort and colleagues (2019). Before all test trials, athletes were instructed to give maximal effort and perform each exercise as they would during regular training sessions with University's performance coaches. Verbal encouragement was provided during each test trial with approximately one minute of rest between trials.

During the CMJ, GRF data were collected with two force plates (AMTI) at 1,000 Hz, whereas during the IMTP, GRF data were collected with only one force plate (Kistler) at 1000 Hz. All GRF data were smoothed with a fourth-order zero-lag Butterworth filter of 15 Hz. The filtered GRF data from the two force plates during the CMJ were summed into a single GRF vector. In addition, the GRF time-series data were normalized to 101 data points to represent 100% of the CMJ movement phase. Movement onset was defined as the point where the filtered GRF fell below 95% of body weight and the end of the movement was defined as the point where the filtered GRF fell below 10 newtons. Peak GRF during each IMTP trial were also extracted. All GRF data were normalised to the athletes' body mass.

The time-normalised GRF time-series data from the GRF were used as input to a PCA. Input data were normalised, and the eigenvector decomposition algorithm was used to extract principal components (PC) and the variance accounted for (VAF) by each PC. PC scores were then calculated for each CMJ trial. Within-subject averages were calculated from data of all successful CMJ and IMTP trials, and used for all statistical analyses.

Associations between peak IMTP force and PC scores were investigated with a correlational analysis. Due to the violation of normality, Spearman's rho correlations were used to calculate the associations between peak IMTP force and each of the PCA scores. Bootstrapping with 1,000 replicate samples was used to increase the robustness of the analyses and allow for reporting of bias corrected and accelerated (BCa) 95% confidence intervals. Other than the PCA, all other analyses were performed with SPSS 26.0.

RESULTS: From the 19 participants, 52 CMJ and 57 IMTP trials were analysed. From these trials, group mean and standard deviations for IMTP peak force and CMJ height were 31.7 ± 3.4 N/kg and 28.0 ± 4.9 cm, respectively. The PCA indicated that three PC could explain 91.7% of the variance in GRF curves during the CMJ (Figure 1). The correlation analysis highlighted multiple significant associations between independent and dependent variables (Table 1).

DISCUSSION: The PCA extracted three patterns from the GRF time series data. The first pattern captured variations in the GRF amplitude during the unweighing phase and in the peak GRF, where greater unweighing was also associated with greater peak GRF during the eccentric phase (i.e., pattern of (+) PC scores). The second pattern captured variations in the overall peak GRF and the presence of a bimodal GRF profile, where lesser overall GRF were also associated with a bimodal GRF profile and greater overall GRF were associated with a unimodal profile (i.e., (-) PC scores and (+) PC scores, respectively). Interestingly, the second pattern was also correlated with the discrete peak RFD during the eccentric phase of the CMJ. Lastly, the third pattern captured variation in the duration of the unweighing phase and in the GRF during the latter part of the concentric phase., where a shorter unweighing phase was also associated with greater concentric phase (i.e., pattern of (+) PC scores). Interestingly, the third pattern was also correlated to CMJ jump height.

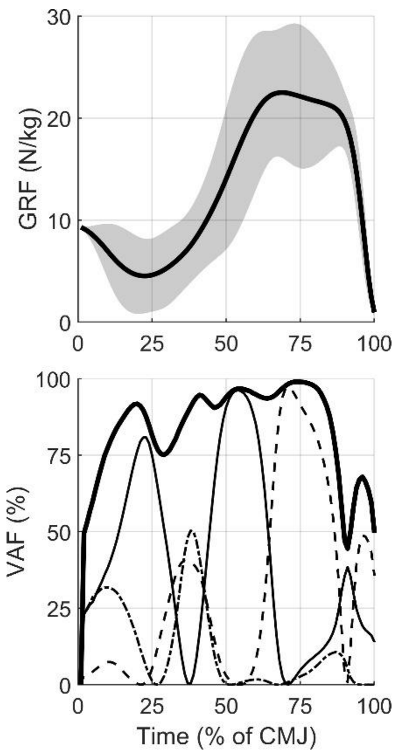

Figure 1: Ensemble average (mean±SD) for body-mass normalised ground reaction force (GRF) time series data during CMJ (top panel). Variance accounted for (VAF) of the GRF time series data by the principal components (bottom panel). Total VAF (black line), VAF by PC1 (thin line), VAF by PC2 (dashed line), and VAF by PC3 (dotted line).

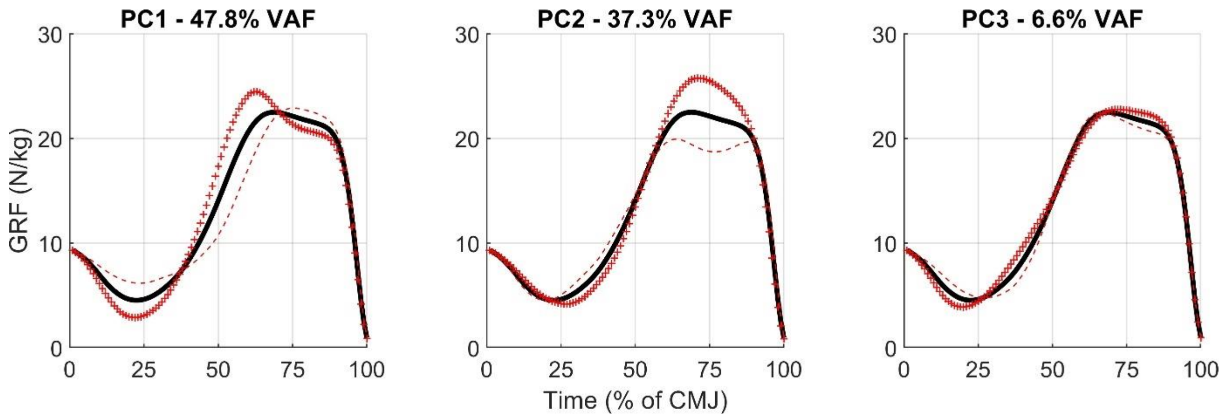

Figure 2: Ensemble average (black line) of body-mass normalised ground reaction force (GRF) time series data during the CMJ along with the effects of each principal component (PC) on the shape of the GRF curves (effects of positive and negative PC scores are illustrated with +/- symbols, respectively).

Maximal strength correlated with the pattern (PC2) that captured variations in peak GRF and the presence of a bimodal GRF profile. The direction of the correlation indicated that players with greater levels of maximal strength exhibited greater overall peak GRF and a unimodal GRF profile. In addition, players with greater maximal strength also exhibited a GRF profile with greater discrete peak RFD during the eccentric phase of the CMJ. It is interesting that greater maximal strength was not positively correlated with any greater CMJ performance variables (e.g. Jump Height; ρ = 0.371; 95% CI = -0.141 – 0.786; *p*-value = 0.118), as this is partly in conflict with the findings of Thomas et al. (2015) that illustrated a relationship to CMJ peak force and peak power but not jump height. That said, another GRF pattern (PC3) was correlated to CMJ performance. This pattern captured the duration of the unweighing phase and the GRF during the latter part of the concentric phase. The direction of the correlation indicated that players with a shorter unweighing phase and greater GRF during the latter part of the concentric phase also exhibited greater CMJ performance. Kennedy and Drake exhibited a similar result in their work, in that higher jumpers were able to maintain higher forces during this portion of the movement, regardless of individual jump profiles (unimodal vs bimodal).

Table 1: Spearman's rho (*ρ*) correlations and 95% confidence intervals (95% CI) between principal component (PC) scores and isometric mid-thigh pull (IMTP) and countermovement jump (CMJ) variables.

PC Score	IMTP and CMJ Variables	*ρ*	*p-value*	95% CI	
PC1	*IMTP Peak Force*	*0.019*	*0.937*	*-0.466*	*0.493*
	CMJ Jump Height	*0.245*	*0.312*	*-0.246*	*0.627*
	CMJ Peak Force	*-0.216*	*0.375*	*-0.623*	*0.271*
	CMJ Peak RFD	*0.346*	*0.147*	*-0.130*	*0.713*
	CMJ Peak Power	*-0.289*	*0.229*	*-0.731*	*0.240*
PC2	***IMTP Peak Force***	***0.544***	***0.016***	***0.071***	***0.844***
	CMJ Jump Height	*0.127*	*0.604*	*-0.381*	*0.681*
	CMJ Peak Force	*0.540*	*0.017*	*-0.050*	*0.912*
	CMJ Peak RFD	***0.716***	***0.001***	***0.455***	***0.852***
	CMJ Peak Power	*0.395*	*0.094*	*-0.033*	*0.684*
PC3	*IMTP Peak Force*	*0.128*	*0.601*	*-0.416*	*0.654*
	CMJ Jump Height	***0.514***	***0.024***	***0.250***	***0.694***
	CMJ Peak Force	*-0.382*	*0.106*	*-0.803*	*0.265*
	CMJ Peak RFD	*0.047*	*0.847*	*-0.487*	*0.556*
	CMJ Peak Power	*-0.146*	*0.552*	*-0.602*	*0.364*

*Significant rho values with $p \leq 0.05$ and 95% CI that do not contain 0 are presented in **bold**.

CONCLUSION: Maximal strength is associated with a specific GRF pattern during the CMJ in our sample of female collegiate lacrosse athletes. In addition, CMJ performance was correlated with a different GRF pattern, which was interestingly independent from the other GRF pattern that correlated to maximal strength. Whether these conclusions apply to males or athletes in other sports should be explored in the future. From an applied perspective, the use of PCA on movement data gives practitioners additional insight into the dynamics of movement patterns that cannot be provided through analysis of discrete variables.

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